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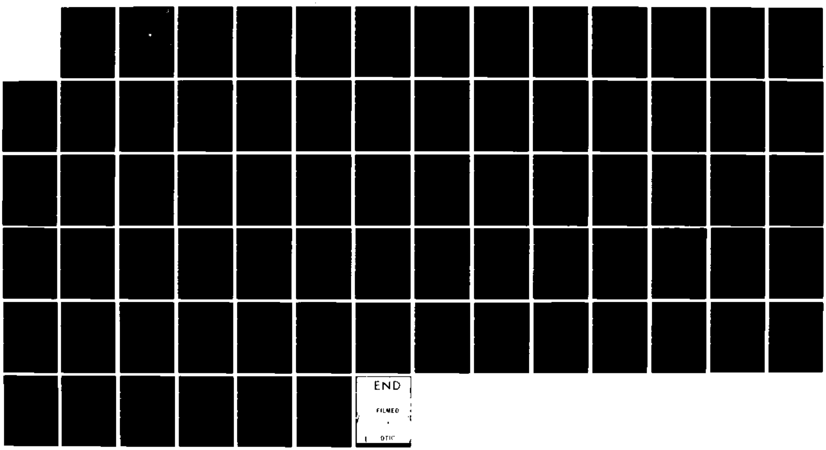

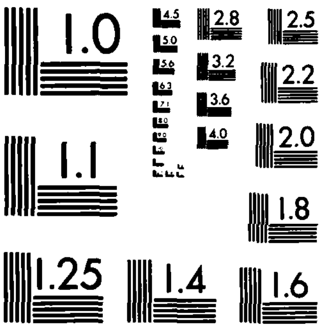

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Deriving Corrections to FNOC Surface Heat Flux Estimates for Use in North Pacific Ocean Predictions

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September 1982

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The specification of the surface heat flux is essential for synoptic and seasonal prediction of the upper ocean thermal structure. Estimates of the surface heat flux have been prepared for the central North Pacific during January 1976 through April 1979 using archived fields from the Fleet Numerical Oceanography Center (FNOC) atmospheric prediction model. Monthly accumulations of the surface heat flux are compared with the change in heat content above 200 m derived from temperature analyses of the North Pacific Experiment TRANSPAC

ship-of-opportunity program. Systematic differences are found between the accumulated heat flux fields and the oceanic heat content change. Some of the differences are due to excessively large changes in ocean heat contents above a fixed level. However, our earlier studies have suggested a bias of excessive upward surface heat flux, especially along the southern boundary of the domain. Assuming local heat balance over a 36-month period, a correction field to the FNOC surface heat flux estimates is derived. Separate correction fields for the heating and cooling seasons demonstrate a seasonal variation in the accumulated heat flux versus heat content change values. Thus, six bimonthly correction fields to be added to the FNOC heat fluxes are prepared to enable these heat fluxes to be used for ocean prediction.

CONTENTS

ABSTRACT

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1. INTRODUCTION

Prediction of the upper ocean thermal structure requires a specification of the surface heat fluxes. The time scale on which the sensible and latent fluxes, plus the incoming and outgoing radiative fluxes, must be specified is dependent on the oceanic phenomena and the type of model. Heat flux values resolved on a time scale of 3 hours or less must be provided if the diurnal variation in the atmospheric forcing is an important consideration in the evolution of the upper ocean thermal structure (Garwood, 1977). Considerable evidence has been accumulated (e.g., Elsberry and Camp, 1978; Camp and Elsberry, 1978; Elsberry and Raney, 1978; Elsberry and Garwood, 1978; and others) that the upper ocean thermal structure responds significantly to atmospheric synoptic-scale forcing. On seasonal time scales, the surface heat flux is accumulated in the upper ocean layers during spring and summer, and subsequently removed during autumn and winter.

Ocean mixed layer models provide a means of demonstrating the two ways in which the surface heat fluxes affect the prediction of ocean thermal structure profiles (Niiler and Kraus, 1977). Consider a well-mixed layer of variable depth, h, with temperature, T. The heat content (H) per unit area in a layer of depth (h) is

$$H = \int_{-h}^{0} \rho C_p T(z)\,dz \tag{1}$$

where ρ is the density, C_p is the specific heat, and z is the depth below the surface. The change in heat content of the mixed layer is

$$\frac{d\,(\rho C_p Th)}{dt} = \frac{\rho C_p h\,dT}{dt} + \frac{\rho C_p T\,dh}{dt}, \tag{2}$$

because the changes in ρ and C_p are relatively small. Solving for the temperature change from the first term on the right side of (2) gives

$$\frac{dT}{dt} = \frac{1}{h}\frac{d(Th)}{dt} - \frac{T}{h}\frac{dh}{dt} = \frac{1}{\rho C_p h}\frac{dH}{dt}. \tag{3}$$

In mixed layer models (e.g., Garwood, 1977), the last term is written as

$$\frac{dh}{dt} = - \frac{\Lambda \, \overline{w'T'}(-h)}{\Delta T} - W(-h) \, ,$$

where $\overline{w'T'}(-h)$ is the vertical turbulent heat flux at the base of the mixed layer and Λ, the Heaviside function, is defined as

$$\Lambda = 0 \text{ for } \frac{dh}{dt} < 0 \, , \qquad (4)$$

$$= 1 \text{ for } \frac{dh}{dt} > 0 \, .$$

The vertical current speed, $W(-h)$, at the base of the mixed layer will be neglected. This relationship indicates that entrainment mixing, and thus the downward heat flux at base of the layer, is only associated with deepening layers. The fraction of turbulent kinetic energy that is available for entrainment mixing in the Garwood model is dependent on both the surface friction velocity and the surface buoyancy flux, which is determined partly by the surface heat flux. Consequently, the surface heat flux contributes to both terms in (3). The effect in the first term is reflected directly in the change in heat content due to the surface flux. The thermal structure is strongly dependent on the vertical redistribution of the heat via entrainment mixing, which is partly due to the upward surface heat flux.

We conclude that specification of the surface heat flux is an essential factor for prediction of anomalous ocean thermal structure. In the next section, we will briefly review the methods available for estimating the surface heat flux over the ocean. In the following section, we examine the role of the surface heat flux in the oceanic heat budget. We then derive a correction field to remove a bias in the surface heat flux that would be detrimental to ocean thermal structure prediction.

2. SPECIFICATION OF THE SURFACE HEAT FLUX

The bulk aerodynamic method for calculating the sensible and latent heat fluxes involves the surface wind field and the differences in temperature and specific humidity be-

tween the sea and the air. Calculations of the incoming and outgoing radiative fluxes require knowledge of the cloud cover as well as the solar altitude. An example of a system for estimating the surface heat flux from ship observations is given by Clark, et al. (1974), Bunker (1976) and Clark (1981). A common approach is to calculate the surface flux from each ship report and then average over some space and time interval. For example, all ship observations taken during a month within 5° latitude and longitude may be used to represent the average heat flux in that domain. Husby (1980) has compared the anomalous heat flux over six-month periods at Ocean Weather Station V (34°N, 164°E) with the estimate based on merchant ship observations within a 4° quadrangle. He concludes that the merchant ship reports must be carefully screened prior to the heat flux computations.

The accuracy of this method is clearly dependent on the number of observations. There is no assurance that the reports will be randomly distributed in space or time. One problem appears to be a "fair weather bias" because the ships tend to avoid bad weather. Barnett (1981) indicates that a set of heat fluxes in the central North Pacific Ocean estimated by this method had a bias of 30-45 W m^{-2}, which would result in an excessive estimation of the heat flux into the ocean.

An estimate of the monthly heat flux is not sufficient for short-term ocean prediction, which requires information on diurnal, or at least synoptic, time scales. Synoptic maps of heat flux are difficult to analyze because of the sparsity of ship observations. An indirect method is proposed here. The atmospheric prediction models also require a calculation of the heat flux at the ocean surface. The heating package for the Fleet Numerical Oceanography Center (FNOC) model involves bulk aerodynamic calculations of the latent and sensible heat fluxes, plus radiative fluxes that are a function of the model-estimated cloudiness (Kesel and Winninghoff, 1972).

Our basic hypothesis is that the FNOC atmospheric prediction model heating package can provide the heat fluxes necessary for ocean prediction experiments. Gallacher (1979) has described the method used for extracting hourly heat flux estimates from the FNOC archives. Elsberry, Gallacher and Garwood (1979) have used these heat fluxes to predict the ocean thermal structure changes during the autumn of 1976. Budd (1980) also used these fields in an attempt to predict the spring transition from the winter to the summer regimes in the central North Pacific Ocean. Budd found a systematic bias with a too large upward heat flux near 30°N. Recently, Steiner (1981) also found a systematic bias in these heat flux estimates in the region between Hawaii and San Francisco.

The purpose of this paper is to describe a correction field to the FNOC surface heat flux fields to permit their use in ocean prediction experiments. As in the case of Budd (1980) and Steiner (1981), the approach is to derive a correction field that assures a long term (annual or longer) heat balance in the upper ocean. Analyses by Waite and Bernstein (1979) of the ocean thermal structure observations in the TRANSPAC ship-of-opportunity program are used to calculate the time changes in oceanic heat content. These are compared with the accumulated surface heat fluxes derived from the FNOC files. We then derive the correction to the monthly surface heat flux that is necessary to assure local heat balance over the 1976-1978 period. In the next section we review briefly some tests of the local heat balance assumption. It is only on the very long time interval that we assume local heat balance. We do not require or insure local heat balance on monthly or shorter time intervals over which we are doing prediction experiments.

3. OCEAN HEAT BUDGET STUDIES

The general purpose in this section is to determine the relative importance of the surface heat flux in the upper ocean heat budget. Our primary interest is in open-ocean

regimes that would be similar to the conditions in the North Pacific Experiment (NORPAX) Anomaly Dynamics Study (ADS) region. We do not consider regions of boundary currents or near-equatorial areas in which horizontal and vertical advection are likely to be significant. The space and time scales of interest are greater than 1000 km and one month.

Many comparisons have been made between the seasonal changes of heat content of the upper ocean and the accumulated heat flux at the surface. Bryan and Schroeder (1960) compared the heat content calculated from North Atlantic BT data with the surface heating estimated by Budyko (1955). They found that the surface heating on a seasonal basis was about 20% less than the change in heat content in the region between 20°N and about 50°N. By contrast, Bathen (1971) found that the surface heat exchange estimates of [illegible]rtki (1966) could account for only 29% of the local m[illegible]hly change in heat content in the North Pacific Ocean. Gi[illegible] and Niiler (1973) propose that the heat input average[illegible] [illegible]er large areas and times is mainly stored locally, and horizontal advection by the mean flow is not particularly important. They also cite comparisons by Tabata (1965) and Robinson (1966) using Ocean Weather Ship data which suggest that most of the heat input changes are stored locally. Gill and Niiler further suggest that the inaccuracy of the heat flux estimates over large areas away from Ocean Weather Ships is the likely cause of some of the departure from local heat balance.

A careful study of the upper ocean heat budget near OWS P based on two weeks of high-quality observations during the Mixed Layer Experiment (MILE) has been reported by Davis, et al. (1981). They found that a one-dimensional upper layer heat budget may be closed acceptably if the temperature is well-sampled, and if the vertical velocity in the seasonal thermocline is also taken into account.

A recent study by Barnett (1981) used AXBT's along 158° and 170°W between 30° and 50°N at approximately monthly intervals to estimate the heat budget. Barnett concludes that

approximately 90-95% of the variance in the seasonal change of heat storage can be accounted for by the air/sea heat exchange. Horizontal and vertical advection were of limited and no use, respectively, in reproducing the seasonal cycle variance. Barnett also concludes that prior heat-budget studies that used an arbitrary lower depth in the estimation of heat content may have inadvertently included variance on different space and time scales. Finally, Barnett suggests that the inability to explain adequately the anomalous heat content changes in the central Pacific is likely due to imprecise knowledge of the source terms in the heat budget.

Our earlier studies (Elsberry et al., 1979; Budd, 1980; Steiner, 1981) have used an oceanic heat budget to determine the feasibility of using the FNOC heat flux estimates for ocean prediction. In each case, the imbalances appear to be systematic in space and time. Large, short-term imbalances are likely due to ocean observational sampling errors and to using an arbitrary lower depth in the estimate of heat content (Barnett, 1981). However, the long-term, systematic error is likely due to a bias in the FNOC heat flux estimates. In the following sections, we derive an appropriate correction field to be added to the FNOC heat flux estimates to remove the long term bias.

4. CALCULATION OF THE OCEAN HEAT BUDGET

Monthly mean temperatures during 1976-1979 have been objectively analyzed by White and Bernstein (1979) based on TRANSPAC ship-of-opportunity XBT's only. Analyzed temperatures are available on a 2° latitude by 5° longitude grid at 0, 20, 40, 60, 90, 120, 150, 200, 250, 300 and 400 m. The general domain of the heat budget calculations is from 30° to 50°N and from 170°E to 130°W. However, the number of observations in the northwest and southwest corners of the grid are insufficient to provide reliable estimates during some months. Consequently, these areas are eliminated from the following analysis, and will appear as cross-hatched areas on all figures.

To calculate the heat content as in (1), the objectively analyzed temperatures are first interpolated to 5 m depths. The heat content is actually calculated relative to the 200 m temperature, with the intent of removing some of the change in heat content due to vertical displacements of the thermocline. Barnett (1981) has suggested that selection of an arbitrary depth such as 200 m may introduce additional variance into the heat content calculation due to internal waves, tides and so forth. Inspection of month-to-month heat content values does reveal time changes which are much larger than can be reasonably accounted for by surface heat fluxes. Large positive time changes tend to be followed by large negative changes. Thus, time intervals of either two or three months have been tested in the estimate of the oceanic heat content change,

$$\Delta H = H(t + \Delta t) - H(t) \ . \tag{5}$$

We expect ΔH to be positive during the period of net downward surface heat flux (roughly between April and September) and negative during the period of net upward flux. The monthly TRANSPAC analyses are assumed to apply on the 15th of each month. If Δt is two months in (5), then ΔH will also apply at the 15th of the month. For example, the difference between the March 1976 and the January 1976 heat content fields would be applied at the middle of February. Notice that this is the first possible value that can be calculated because the analyses begin in January 1976. However, if Δt is three months in (5), then ΔH will apply at the mid-point of this interval. Thus, the first possible difference would be between April 1976 and January 1976, and it would apply on 1 March 1976. The advantage of the longer time interval is that shorter period fluctuations in heat content tend to be averaged out and one obtains a more consistent measure of the seasonal variation. The disadvantage of the longer time interval is the greater inaccuracy in the finite difference approximation to a derivative. Finally, it is necessary to extend the ΔH calculation into 1979 to obtain three complete annual cycles. In the case of Δt = 2

(3) months, the analyses through February (March) 1979 are used.

Following Emery (1976), the basic heat balance equation may be written as

$$\frac{\partial H}{\partial t} = \frac{W_D}{D}(H - \rho C_p D T) - \vec{V} \cdot \nabla H + Q , \qquad (6)$$

where H is defined as in (1) with -h, the mixed layer depth, replaced by D which is a (constant) depth below the main thermocline. In (6), the first term on the right represents the divergence of heat due to horizontal divergence, $W_D H/D$, and vertical advection $W_D \rho C_p T$. The second term is the horizontal advection of heat and the last term is the surface heat flux. The suggestion by Barnett (1981) and Davis et. al. (1981) that D be the depth of an isotherm below the main thermocline rather than a constant depth results in the divergence term in (6) being zero, and thus eliminates a source of uncertainty from the heat budget. Due to the large vertical sampling interval in the TRANSPAC analyses, we will use D = 200m throughout this study. Thus, we assume the following budget equation

$$\Delta H = \int_0^{\Delta t} Q dt + \text{Residual} = Q_T + \text{Residual} . \qquad (7)$$

The integral sign indicates that the air-sea flux is summed over the same time interval that ΔH is evaluated. Q_T is defined as the surface heating. In the Δt = 2 month example above, the sum would be from 15 January through 15 March. The residual term in (7) includes the remaining terms (physical effects) in (6) that can not be evaluated, plus the errors in estimating the heat content changes and the surface fluxes. If these observational errors are random over a sufficiently long interval, their contribution should be averaged out. In particular, we sum over 36 months (or a small subset if a seasonally varying correction factor is derived) and derive an averaged correction field to be added to the surface heat flux. However, the physical terms may not sum to zero. Persistent vertical and horizontal advection or diffusive effects that accumulate during the period are thus also incorporated into the correction

field. The impact of assuming a local (one-dimensional) heat balance via this long-term correction field will be assessed in the prediction experiments.

The total heat flux Q in (7) may be expressed as

$$Q = Q_s - (Q_b + Q_h + Q_l) , \tag{8}$$

where the subscripts s, b, l and h refer to solar, back, latent and sensible heat fluxes through the sea surface. A description of the calculation of each of these heat fluxes in the FNOC atmospheric prediction model is given in Kesel and Winninghoff (1972). The values of these terms after a one-hour integration of the model are taken to apply at the synoptic map time (00 or 12 GMT). After spatial interpolation to the grid points of the ocean analysis, these instantaneous values are interpolated to hourly values using techniques described by Gallacher (1979). The representation of the solar flux is particularly involved. It is this time series of hourly values of Q_s and Q_u $(= Q_b + Q_h + Q_l)$ that are accumulated in (7). Simply summing the instantaneous 12-h FNOC values would not produce the same sum because we have reconstructed the hourly variation in Q.

An example of a field of ΔH near the beginning of the ocean heating season is given in Fig. 1. Over most (all) of the domain, the heat content change is positive, as expected. A value of 2×10^4 cal cm^{-2} over this two-month period corresponds to an average increase in temperature of 2° C over a depth of 100 m, or 4°C over a depth of 50 m. Less confidence should be given to the values near the northern and southern boundaries of the domain. The primary ship-of-opportunity tracks lie on the great circle route between Japan and the USA west coast ports (White and Bernstein, 1979). During the winter, the tracks tend to be displaced southward, which makes the northern region sampling rather poor. Somewhat the opposite effect occurs during the summer as the ship tracks are extended northward. The objective analysis procedure (White and Bernstein, 1979) used through 1978 would generate values at all gridpoints regardless of whether any observations fell in the vicinity of the

point. Because the deficient points tend to lie toward the north and the south, the fictitious values tend to resemble northward or southward extrapolations from the central region.

The corresponding integrated surface heat flux for this period derived from the FNOC calculations is shown in Fig. 1c. In contrast to the ΔH fields, no extrapolation of the fields toward the domain boundaries is involved in the Q_T field. In the band from 40-50° N, the surface exchange is approximately equal to the observed ocean heat content change, which suggests an approximate local heat balance. However, the net FNOC heat flux continues to be upward between 30-35° N during this period. One can not tell from this diagram whether the daily values of Q_S in (8) are too small, or if the upward surface heat flux (Q_u) is too large. The fact that the maximum values are found near the longitude for which the boundary of the FNOC grid is tangent to the equator (therefore closest to the study region) suggests that the problem may lie in the boundary conditions that are applied.

The difference between ΔH and the cumulative heat flux (Q_T) is shown in Fig. 1 . A light filter, with weights 2-4-2 in latitude and 1-4-1 in longitude, has been passed over this field to reduce small scale noise. Although there are considerable areas with the expected zero values, there are other areas with positive and negative values. In particular, the residual term in (8) is very large along the southern boundary because of the lack of a net downward surface heat flux (Fig. 1).

The complete set of monthly ΔH, Q_T and $\Delta H-Q_T$ values is contained in the Appendix. Since our desire is to obtain a correction field, it is not appropriate to discuss here each of these sets. One general feature is that the Q_T fields have less east-west variation and more north-south variation than do the ΔH fields. There are several possible causes for this feature: (a) the FNOC heat fluxes may not contain an adequate representation of the east-west var-

iations in the anomalous surface fluxes; (b) vertical advective processes associated with ocean eddies are contained in the heat content values relative to a fixed depth; and (c) errors due to inadequate observations or analysis of the ocean heat content. The spring transition regime example in Fig. 1 illustrates one of the worst imbalances in the time series. An excessive upward heat flux also occurs along the southern boundary during autumn. However, the ΔH field is negative (upper ocean heat content diminishing in time) during this period. Consequently, the magnitude and sign of the imbalance may have a seasonal dependence (discussed further in the next section).

Similar sets of ΔH, Q_T and $\Delta H-Q_T$ were also prepared with Δt = 3 months. These fields (not shown) are not directly comparable with the two-month set because of the half-month displacement of the central point. However, the time evolution of the major features using Δt = 3 months can be easily associated with the evolution shown by the Δt = 2 month series. Therefore, only the correction fields based on the 2-month differences will be discussed below.

5. INTERPRETATION OF THE HEAT BUDGET IMBALANCE

Perhaps the most important factor to emphasize regarding these calculations of the local heat budget (8) is that each of the two terms is subject to large errors. As noted above, calculating the heat content changes relative to a fixed depth may produce oscillations equivalent to a 1-2°C change averaged over the entire depth. A faulty XBT could also be the cause of a temperature bias with depth. However, we would expect that the objective analysis technique would tend to eliminate such a bias if other correct profiles are in that region. Based on our earlier studies (Elsberry, et al., 1979 ; Budd, 1980; Steiner, 1981), we expect that the monthly surface heating does not have a sufficiently large seasonal amplitude. There is also a persistent bias toward excessive heat loss to the atmosphere along the southern boundary of the domain.

Because the heat budget imbalances may arise from either term, Table 1 was prepared to indicate the various possibilities that may arise. It is useful to separate the ΔH into separate periods when the ocean heat content is increasing or decreasing. Apart from small calculation errors, one would hope that the corresponding Q_T would be positive (surface heating) or negative, respectively, so that Cases A-B or E-F would apply. One expects approximately an equal distribution between A and B or between E and F if the errors are random. The percentage of gridpoints with monthly $\Delta H-Q_T$ differences exceeding 0.5×10^4 cal cm^{-2} are not evenly distributed between cases A and B or between E and F when the uncorrected Q_T is used in the differences. There is clearly a bias toward cases A and E, which could be attributed to excessive upward heat flux during both the ocean warming and cooling periods. However an approximately equal distribution is obtained when the corrected (see description of six bi-monthly correction fields in the next section) surface heat flux is used in the differences.

A value of 0.5×10^4 cal cm^{-2} corresponds to a heat flux bias of 7.0 cal cm^{-2}hr^{-1} or a temperature bias of .25° C in a 200 m water column. Both of these values are within the expected range of instrument error for the measurements which were used in the analyses. Whereas 65% of all the differences exceed this criterion for the uncorrected heat flux, only 42% exceed the criterion for the corrected heat flux.

Cases C and D in Table 1 are labelled as drastic imbalances because the ΔH and Q_T are of opposite tendencies. A physical explanation for such an event might be the advection of a warm (cold) ocean eddy into the region that has upward (downward) surface heat flux. An example of a computational explanation is found along the southern boundary in Fig. 1 where $Q_T < 0$ when $\Delta H > 0$. The percentages in Table 1 indicate that drastic imbalances are relatively rare during ocean cooling periods (Case D - 1%) when the uncorrected Q_T is used in the differences. However, this is not the case during the ocean warming periods, when a large fraction

of the points have significant upward heat fluxes rather than downward. Since the heat budget for the central Pacific is in an approximate local balance for seasonal time scales (Gill and Niiler, 1973), the percentages for Cases C and D should be less than those for Cases A, B, E and F. This distribution is obtained when the corrected Q_T values are used, but not with the uncorrected Q_T. This is a further demonstration of the need to adjust the FNOC surface heat fluxes.

The alternative of a systematic bias due to the ΔH calculation does not appear likely. Although there are more points with ΔH positive (59%) than negative (41%), this asymmetry is probably within the limits of roughly offsetting periods of ocean warming versus cooling. The imbalances between seasons in Table 1 are not consistent with horizontal advection being a primary cause. One would expect stronger Ekman advection effects during the winter (cooling season), whereas the larger imbalances are found during the summer.

TABLE 1

ΔH versus Q_T

<table>
<tr><th></th><th>$Q_T > 0$
(Downward surface heat flux)</th><th>$Q_T < 0$
(Upward surface heat flux)</th></tr>
<tr><td rowspan="2">$\Delta H > 0$
Ocean warming</td><td>Case A $\Delta H - Q_T > 0$
Inadequate downward Q
Excessive ocean warming
22.4% (26.8%)</td><td rowspan="2">Case C $\Delta H - Q_T > 0$
Drastic imbalance
33.4% (7.3%)</td></tr>
<tr><td>Case B $\Delta H - Q_T < 0$
Excessive downward Q
Inadequate ocean warming
2.9% (20.0%)</td></tr>
<tr><td rowspan="2">$\Delta H < 0$
Ocean cooling</td><td rowspan="2">Case D $\Delta H - Q_T < 0$
Drastic imbalance
1.0% (6.5%)</td><td>Case E $\Delta H - Q_T > 0$
Excessive upward Q
Inadequate ocean cooling
34.6% (16.7%)</td></tr>
<tr><td>Case F $\Delta H - Q_T < 0$
Inadequate upward Q
Excessive ocean cooling
5.4% (22.6%)</td></tr>
</table>

Possible physical association for positive or negative heat budget imbalances given that the heat content or integrated surface fluxes are positive or negative. Percentage of the gridpoints for the 36 monthly maps that fall in each category are indicated. The percentages in parentheses were computed using the corrected total heat flux. Only points with $|\Delta H - Q_T| > 0.5 \times 10^4$ cal cm^{-2} for the two month difference are included in the calculation of the percent.

6. CALCULATION OF CORRECTION FIELD

Our objective is to determine a correction field that may be applied to the Q values in (8) during the ocean prediction experiments. Because the time step in the Garwood model is typically 1 h, it is desirable that the correction be in units of cal cm^{-2} $hour^{-1}$. This is done by converting each of $\Delta H-Q_T$ fields to an hourly rate using the proper number of hours in the time interval. The sign is also changed because the correction is to be added to the Q_T field.

It is not within the scope of this paper to determine the fraction of this correction which will be applied to Q_S versus the remaining three terms in (8). It might be noted that Q_S occurs only during the daytime and this flux is to be distributed exponentially with depth by the prediction model. In contrast, the remaining three terms in (8) apply only at the surface and tend to be positive (upward) throughout the day. Thus, one may expect considerable differences in the upper ocean predictions as the fraction of the correction that is allcted to Q_S is increased.

For simplicity, one desires a single correction field as in Fig. 2. The basic features in this correction field are generally consistent with the pattern shown in Fig. 1a. In particular, the correction reduces the surface heat flux (upward is defined to be positive) along the southern boundary. It can be shown that this correction is equivalent to calculating the residual in (7) using the difference in H between January-February 1979 and January-February 1976, and the Q_T for the entire period. We may also regard the single correction field as the adjustment necessary during each hourly time step of an integration from 15 January 1976 to 15 January 1979. If the correction is applied in this way, we can be assured of conservation of heat at each gridpoint for the entire three year period (assuming no vertical diffusion and no round-off errors).

Each of the 36 maps of $\Delta H-Q_T$ is different from that implied by the single correction field. We noted above that

the seasonal variation in ΔH or Q_T might be associated with a modulation in the difference field. A separate correction field is derived for November through April (Fig. 3a) and for May through October (Fig. 3b). Each of these corrections is summed over the three years and six months, so that a total of 18 values is included in each average. There is clearly a seasonal variation in these two correction fields. The pattern during the heating season (Fig. 3b) is similar to the single correction field (Fig. 2), but the values are larger. The pattern during the cooling season (Fig. 3a) is quite different. Not only are the values considerably smaller than in Fig. 3b, there is more of a north-south orientation of the isolines in the north-central region.

Based on the seasonality in Fig. 3, we also examined further subdivisions into quarterly or bi-monthly correction fields. A decision was then made to adopt the six correction fields in Fig. 4 a-f. It is felt that six maps will give a better representation of the seasonal variation. Inspection of Fig. 4 b-e reveals a basically east-west pattern, whereas the remaining two maps exhibit the north-south orientation. Even though the seasonal variation does not appear to be a sine wave, the six maps appear to provide a relatively smooth transition between the two basic patterns in Fig. 3. There are some non-seasonal features in these correction fields. The largest is found along the western side of the domain. Larger corrections are required during February-March (Fig. 4a) and during August-September (Fig. 4d). The transition between the correction field for December-January (Fig. 4e) and for February-March is especially noteworthy along the western boundary. The regions of positive corrections (additional upward heat flux required) also tend to be somewhat erratic. However, these positive corrections are always small, so they will have little effect on the ocean predictions.

An example of the application of the heat flux correction field at a specific location is given in Fig. 5. The seasonal changes in heat content calculated from the

TRANSPAC analyses have relatively constant values during the heating season. By contrast, the ΔH values during the cooling season tend to reach rather well-defined peaks. The surface heating agrees rather well with the maximum ΔH values during each cooling season. However, the uncorrected heat flux during the warming season is clearly deficient, especially during 1978. Applying the heat flux corrections for this location from Fig. 4 improves the agreement between the surface heating and the ΔH. The major feature to be noticed is that the $(\Delta H - Q_T)$ differences are indeed systematic, so that a single correction in each two-month period tends to improve all three years. One finds periods in which the $\Delta H - Q_T$ remains large after the correction has been applied. This indicates that although we have had to correct the surface heat flux we have not forced the heat budget to be one-dimensional for periods shorter than 36 months. Some examples are the differences during April - June 1976 and during July - August 1978. Another feature in Fig. 5 is that the area between the ΔH and the corrected Q_T curves must sum to the difference between the final and initial H values (February 1979 and January 1976, respectively). This requirement is a consequence of the local heat budget assumption over the 36-month period.

7. SUMMARY

We have prepared six bi-monthly correction fields to be applied to the FNOC heat flux values to be used for ocean prediction. The largest corrections are found generally between 30 and 38 N during April through November. The heat flux bias is evidently not serious for the atmospheric predictions because they are limited to 72 h. However, such a bias can be disastrous (Budd, 1980) for ocean prediction over monthly time periods. The correction fields are averaged over three years (1976-1979). Closure of the local heat budget over the entire period is insured by the use of this correction field. However, this is not true over any shorter time intervals. In particular, fluctuations in heat

content in the monthly TRANSPAC analyses are not accounted for by the long-term correction field.

The success of these correction fields can only be judged by their application in the ocean prediction experiments. Inclusion of the corrections should result in improved predictions. One of the tests will be whether the six bi-monthly correction fields perform better than the two semi-annual correction fields. In some of the correction fields, the east-west variation is not large. It is possible that a correction dependent only on latitude may perform as well. Such a correction would be easier to apply. The numerical ocean prediction experiments necessary to demonstrate the usefulness of the corrections are in progress, and will be reported separately.

ACKNOWLEDGEMENTS

This research has been sponsored by the Naval Ocean Research and Development Agency under contract number N6846282WR20098, Program Element 62759N. The data archiving division of Fleet Numerical Oceanography Center provided the heat flux fields for 1977 through 1979. Steve Pazan provided the heat flux fields for 1976 from the NORPAX data center. Warren White, Buzz Bernstein and Steven Pazan supplied the NORPAX analyses of ocean thermal structure. Computer time was provided by the Church Computer Center of the Naval Postgraduate School. The authors wish to thank C. N. K. Mooers and Bob Haney for comments on the manuscript, which was typed by Ms. Marion Marks and Ms. Tina Cech.

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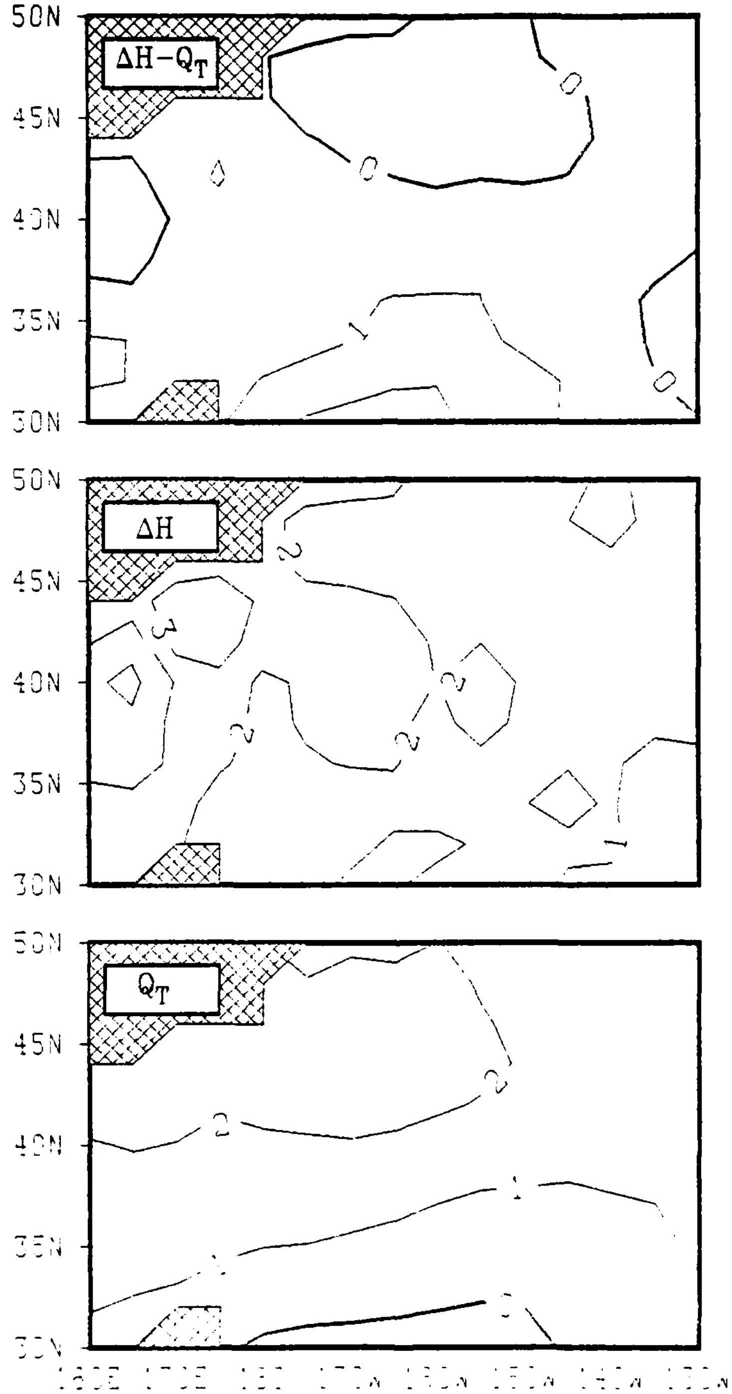

Fig. 1 The difference ($\Delta H-Q_T$) and the change in heat content relative to 200 m (ΔH) and the surface heating (Q_T) between July 1976 and May 1976. Cross-hatched areas have insufficient data for the ΔH analysis. Positive values of ΔH indicate increasing heat content, while positive Q_T indicates a net downward surface heat flux. Units: 10^4 cal cm^{-2} per 2 months.

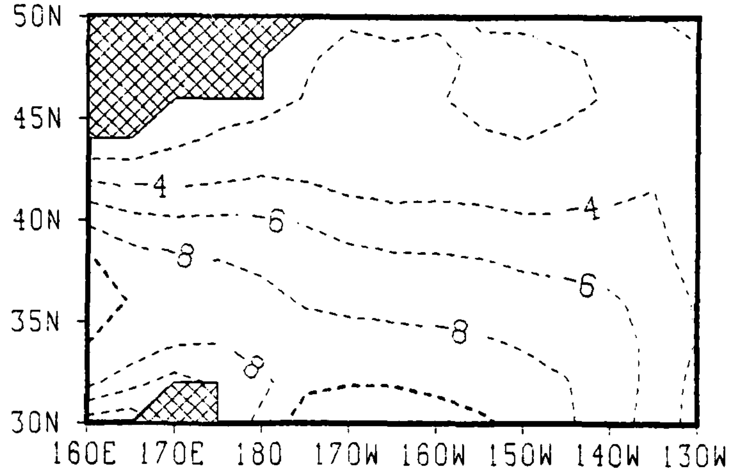

Fig. 2 Correction field (cal cm^{-2} h^{-1}) to be applied to FNOC heat flux fields based on all 36 of the monthly sets of (Δ H-Q_T) evaluated over two-month intervals. Negative values indicate that the upward heat flux is to be reduced by the amount shown.

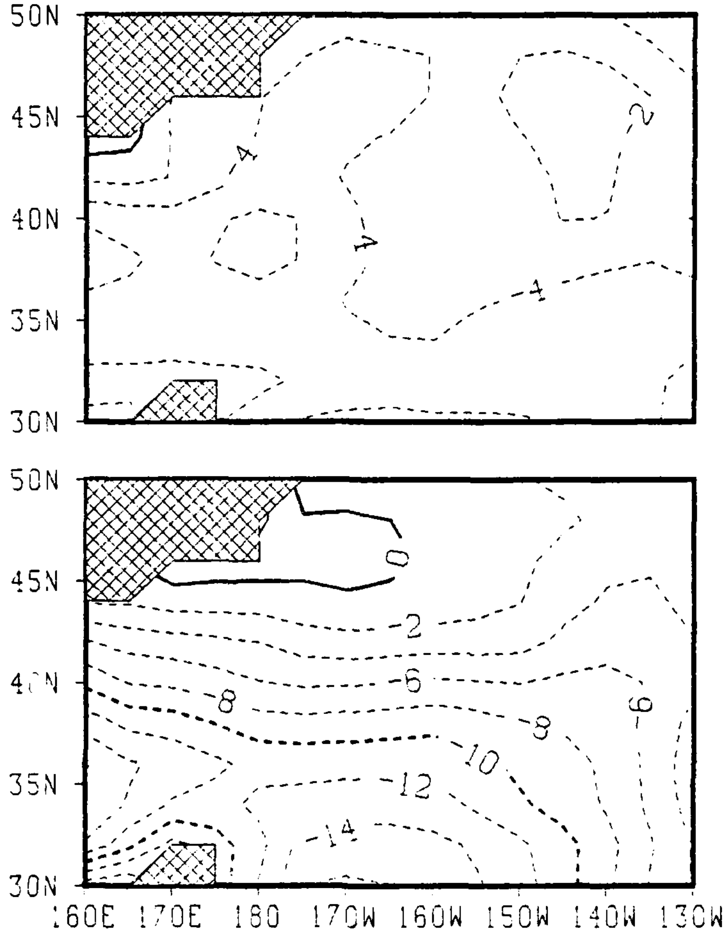

Fig. 3 As in Fig. 2, except separate correction fields for November through April (top) and for May through October (bottom).

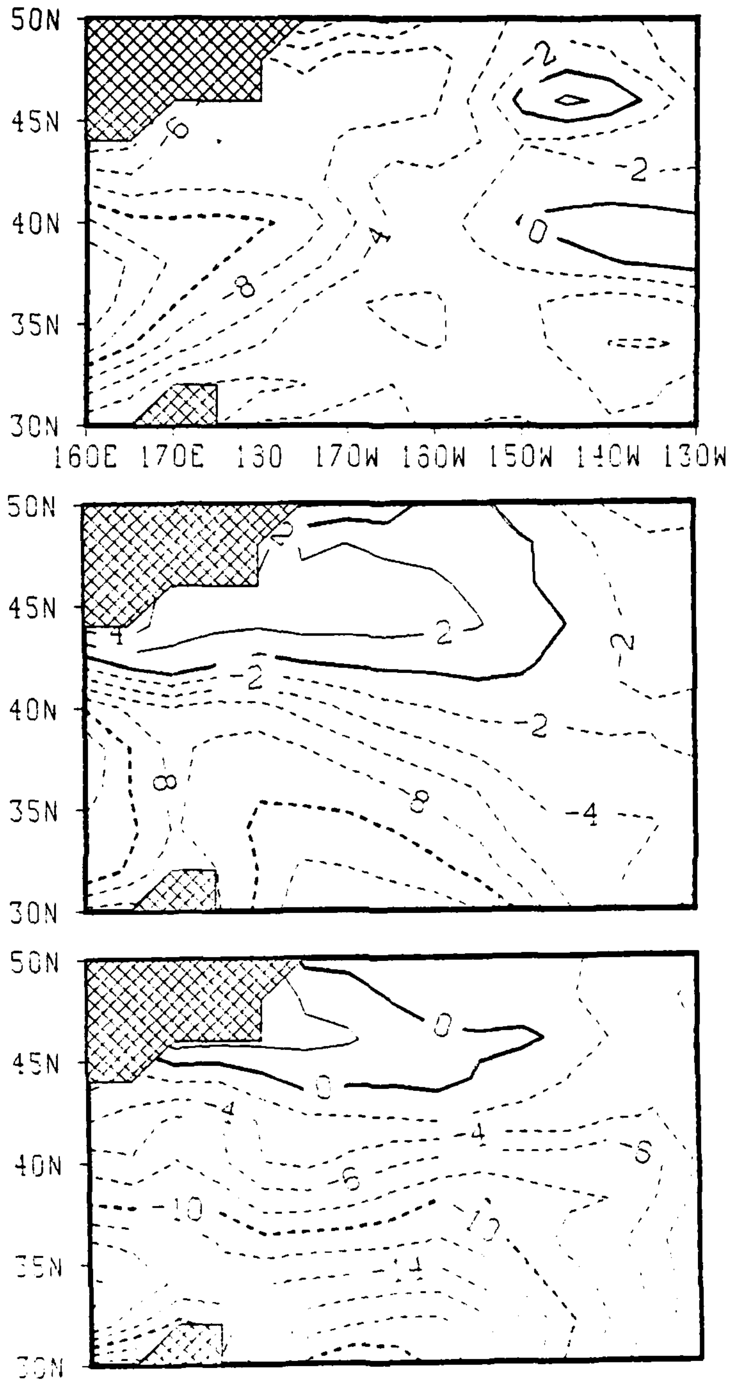

Fig. 4 As in Fig. 2, except bi-monthly correction fields for: February - March (top); April - May (middle); June - July (bottom).

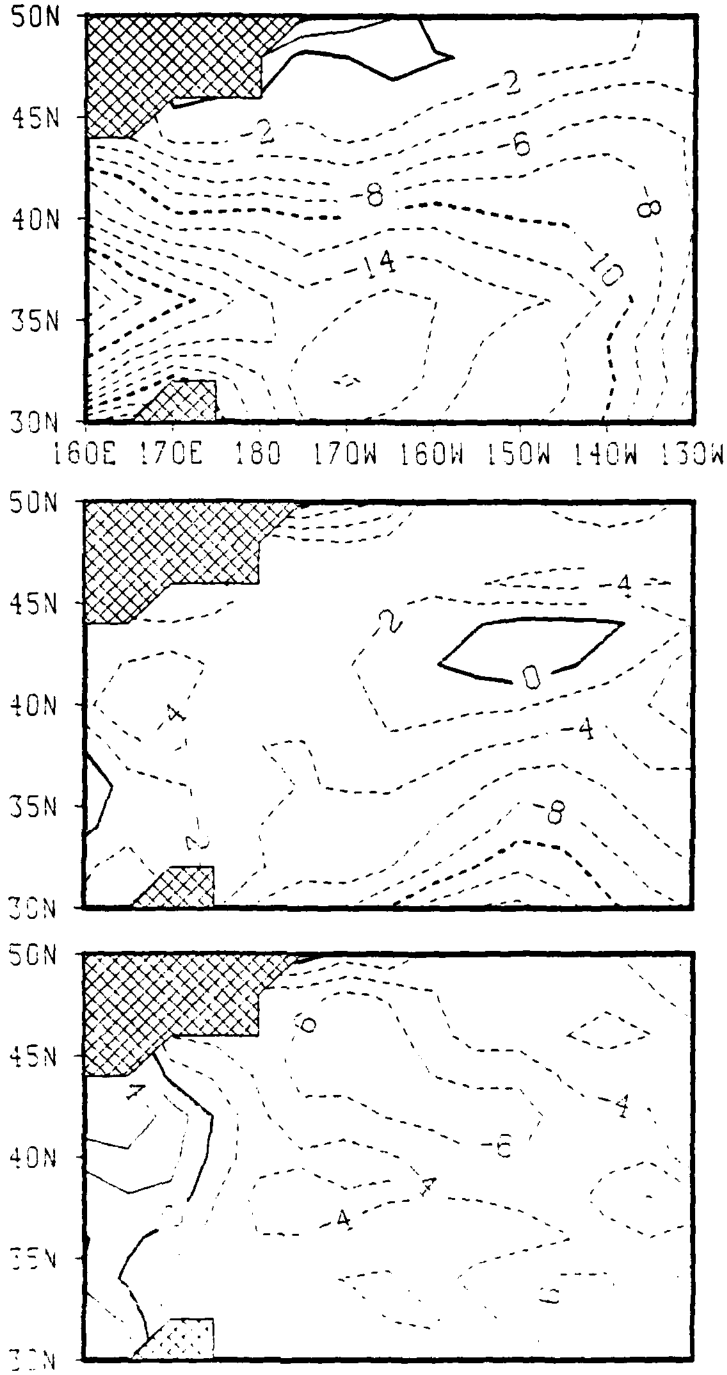

Fig. 4. (continued) As in Fig. 2, except bi-monthly corrections for: August - September (top); October - November (middle); December - January (bottom).

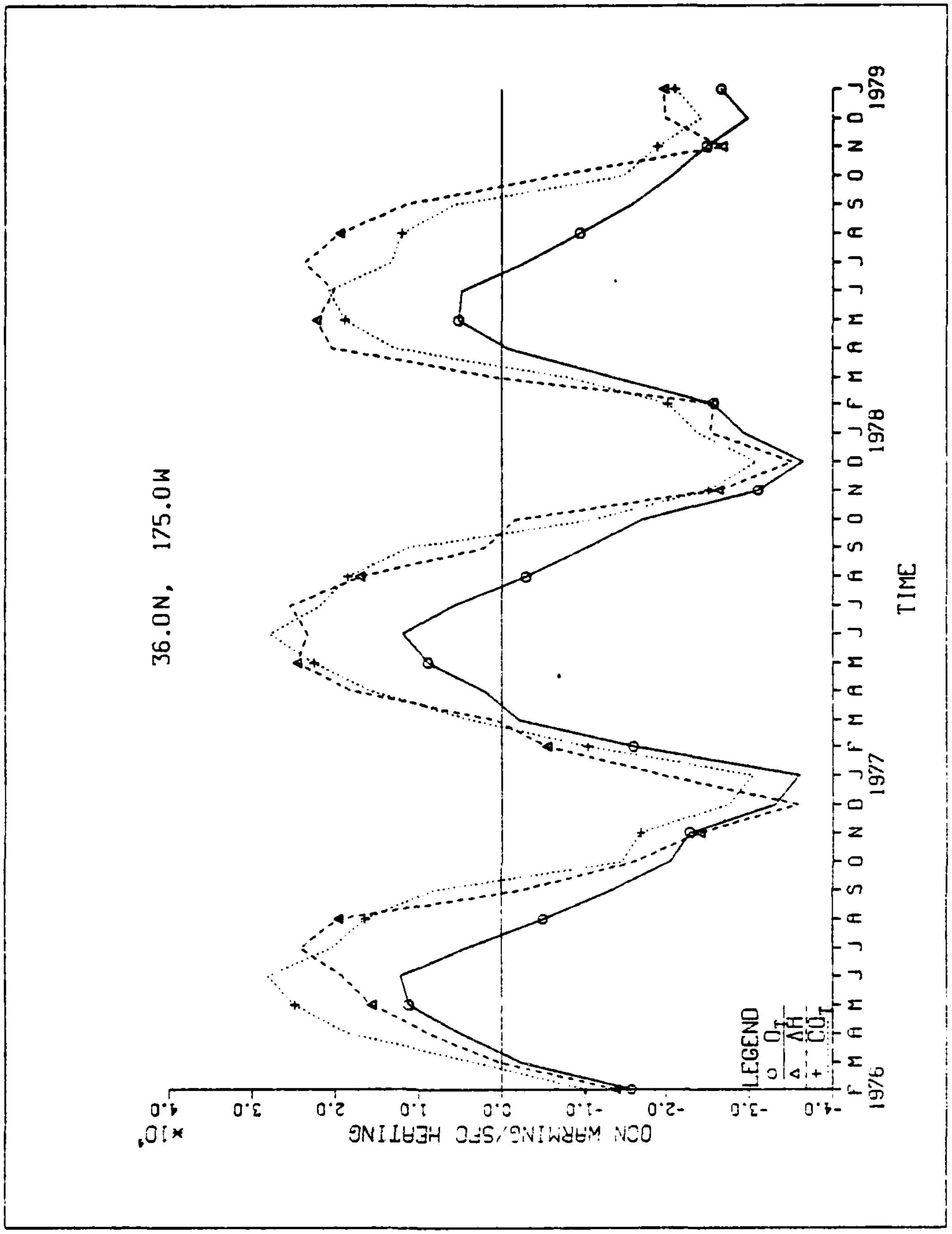

Fig. 5 Time series of changes in heat content (dashed), uncorrected surface heating (solid), and corrected surface heating (dotted) at 36°N, 175°W. CQ_T is the corrected total surface heating. Units are 10^4 cal cm^{-2} over two-month intervals.

Appendix A

MONTHLY SETS OF $\Delta H-Q_T$, ΔH AND Q_T

The monthly sets of $\Delta H-Q_T$, ΔH and Q_T based on two-monthly intervals are included, except for the May - July 1976 set which is in Fig. 1. The form of these diagrams is described in the caption of Fig. 1. Positive values (solid lines) are increasing heat content in time and net surface heating, and conversely for negative values (dashed lines). Zero lines are enhanced.

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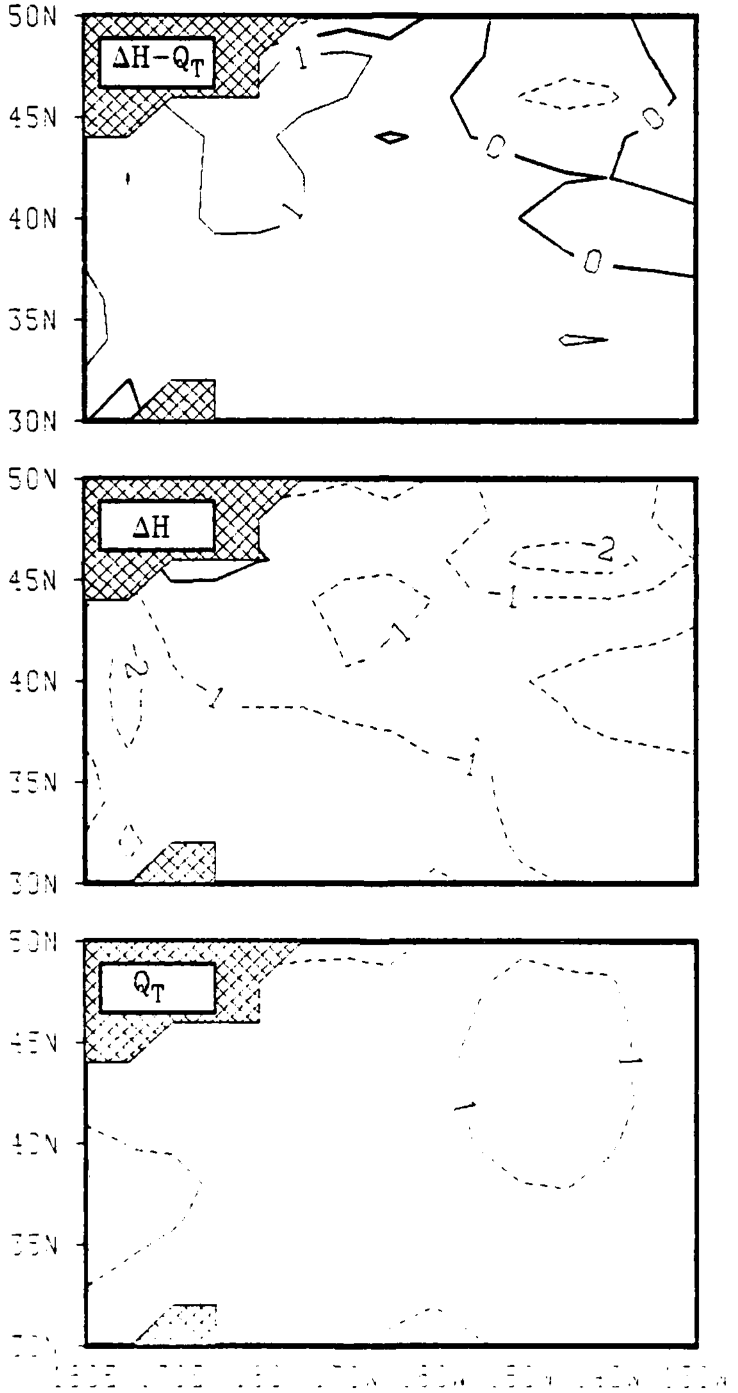

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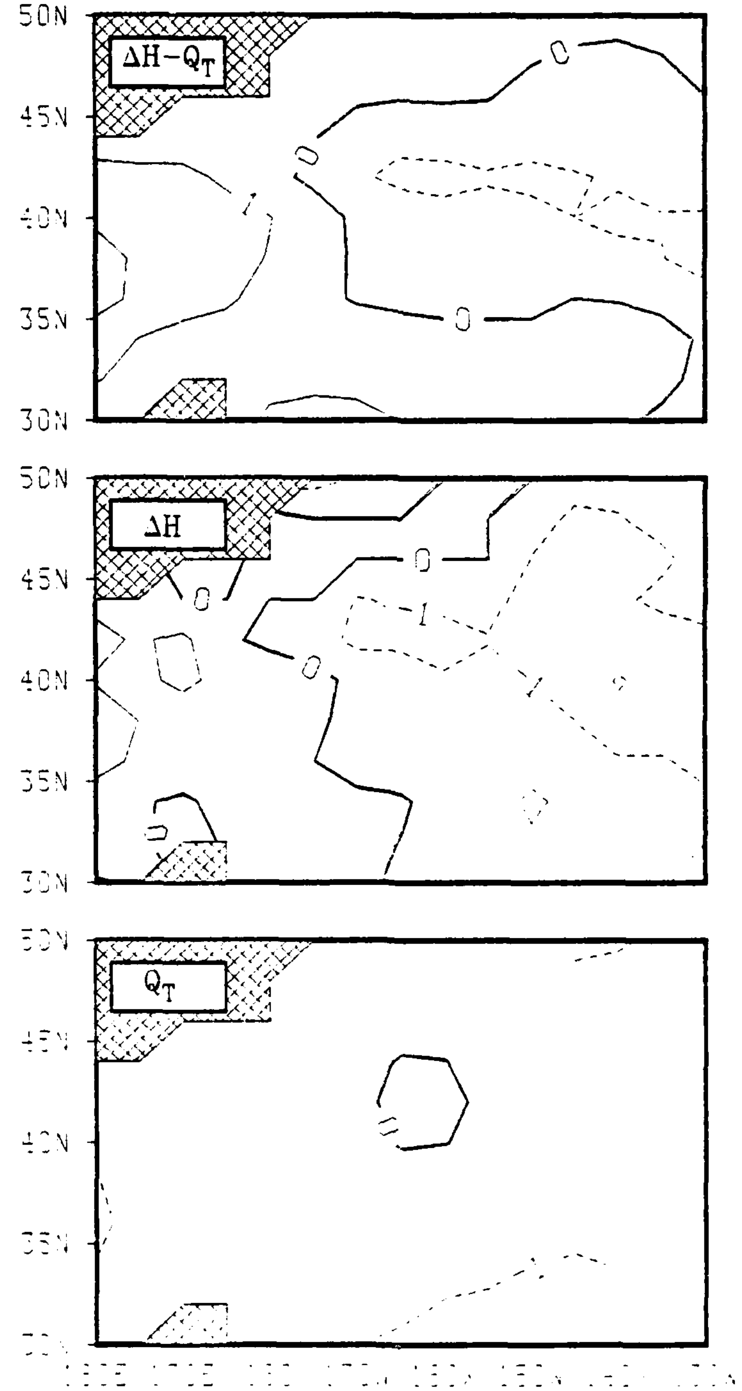

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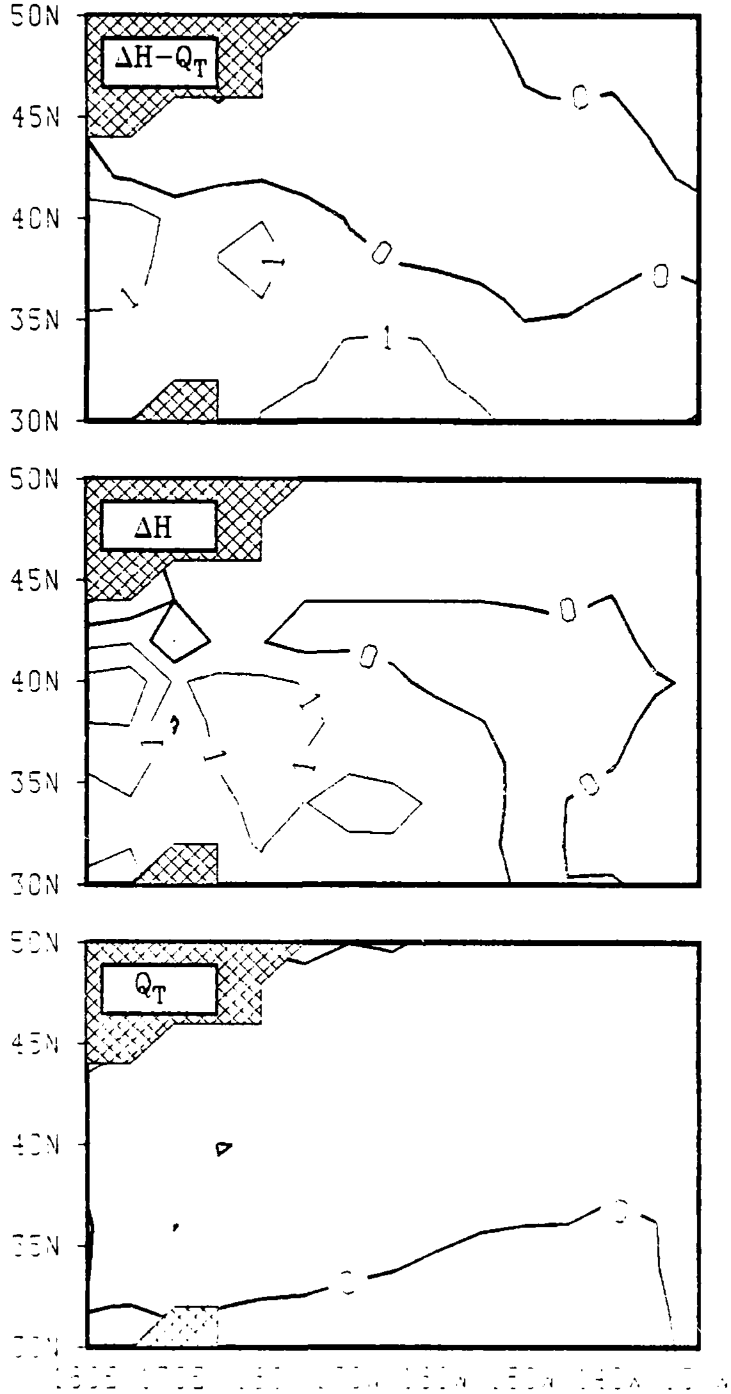

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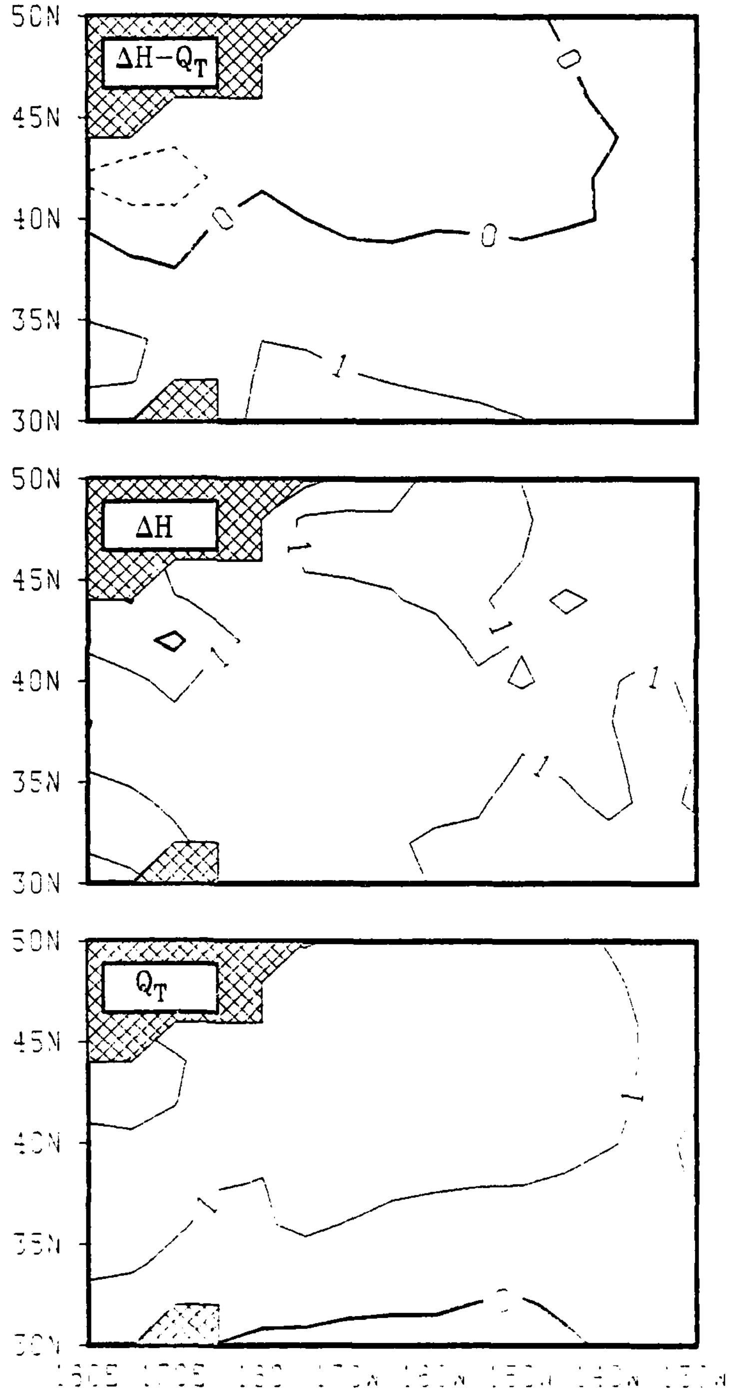

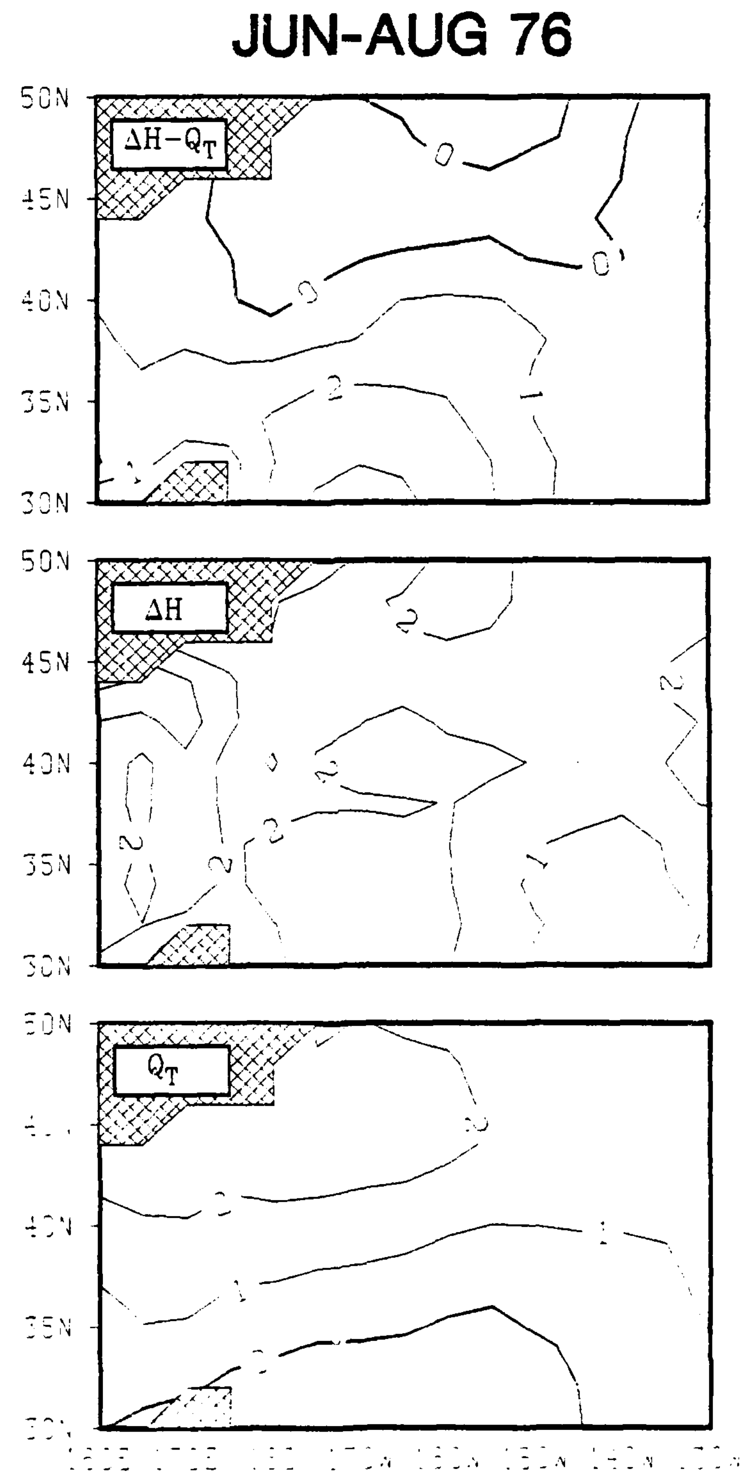

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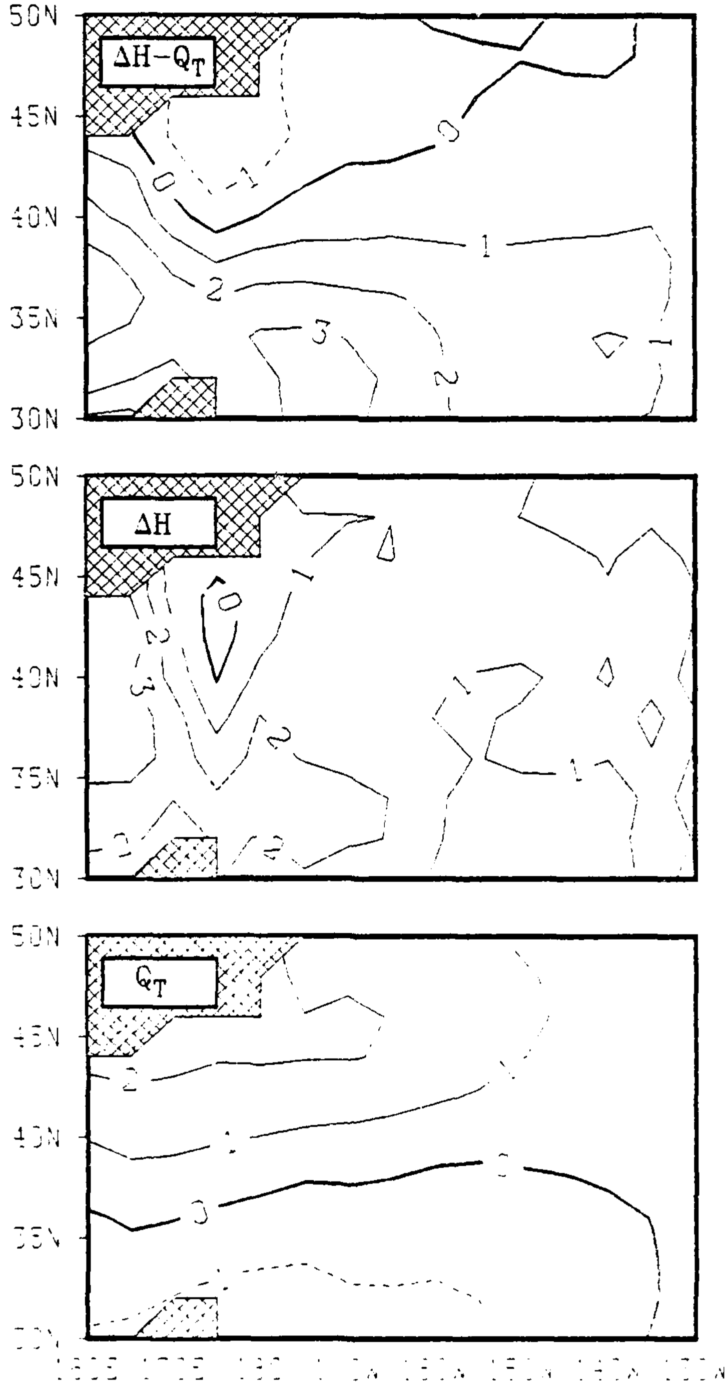

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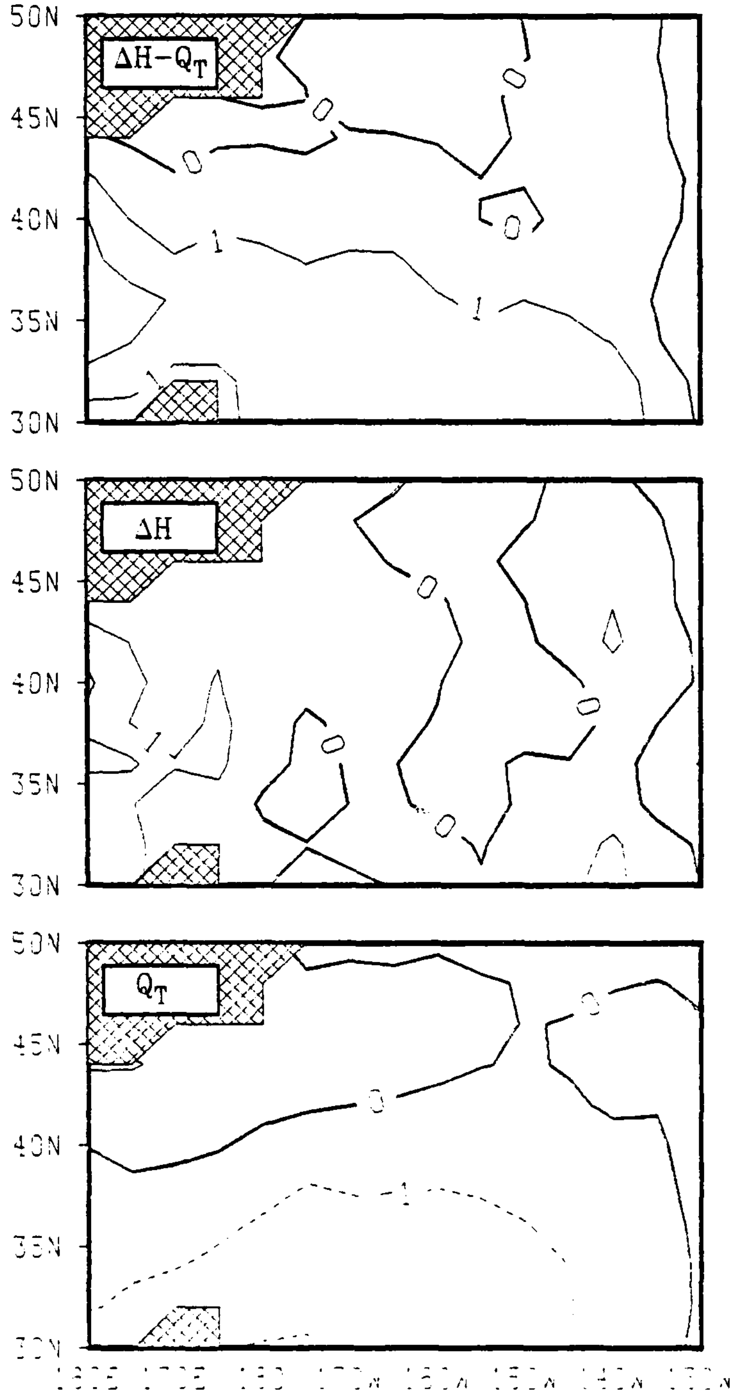

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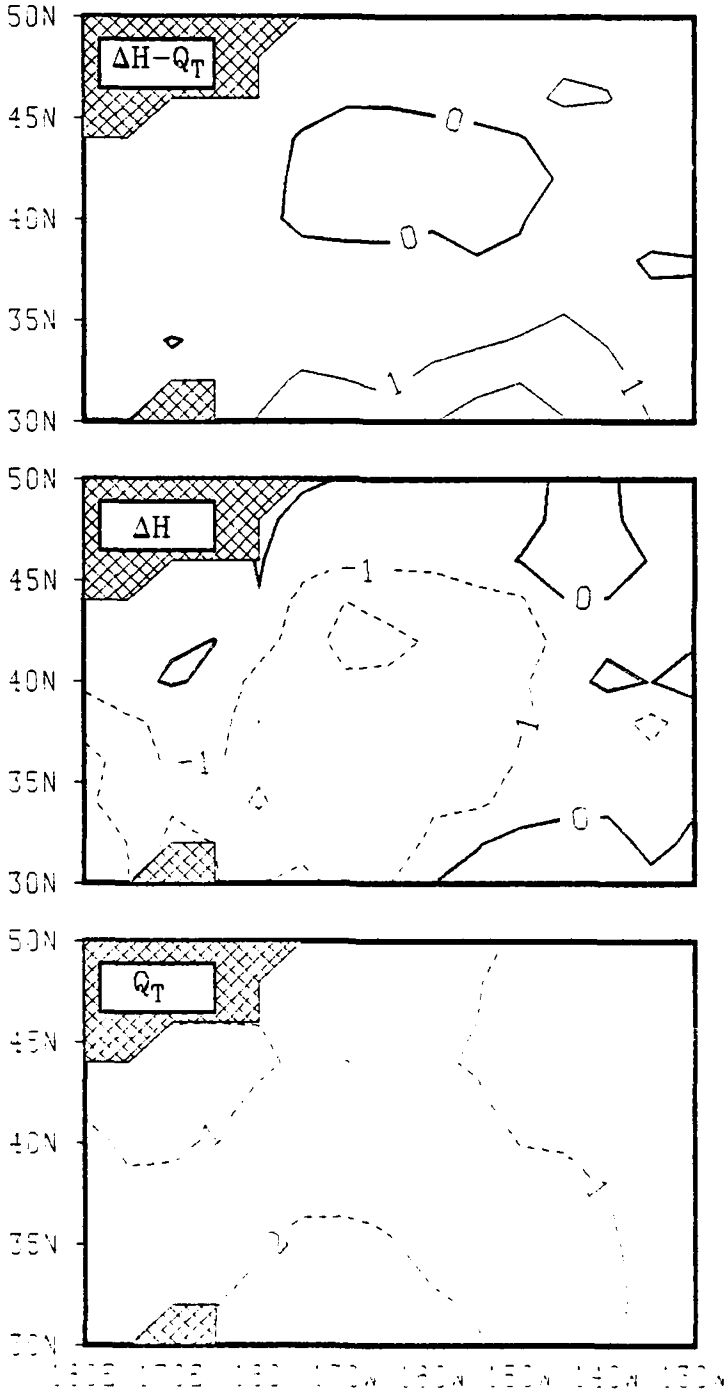

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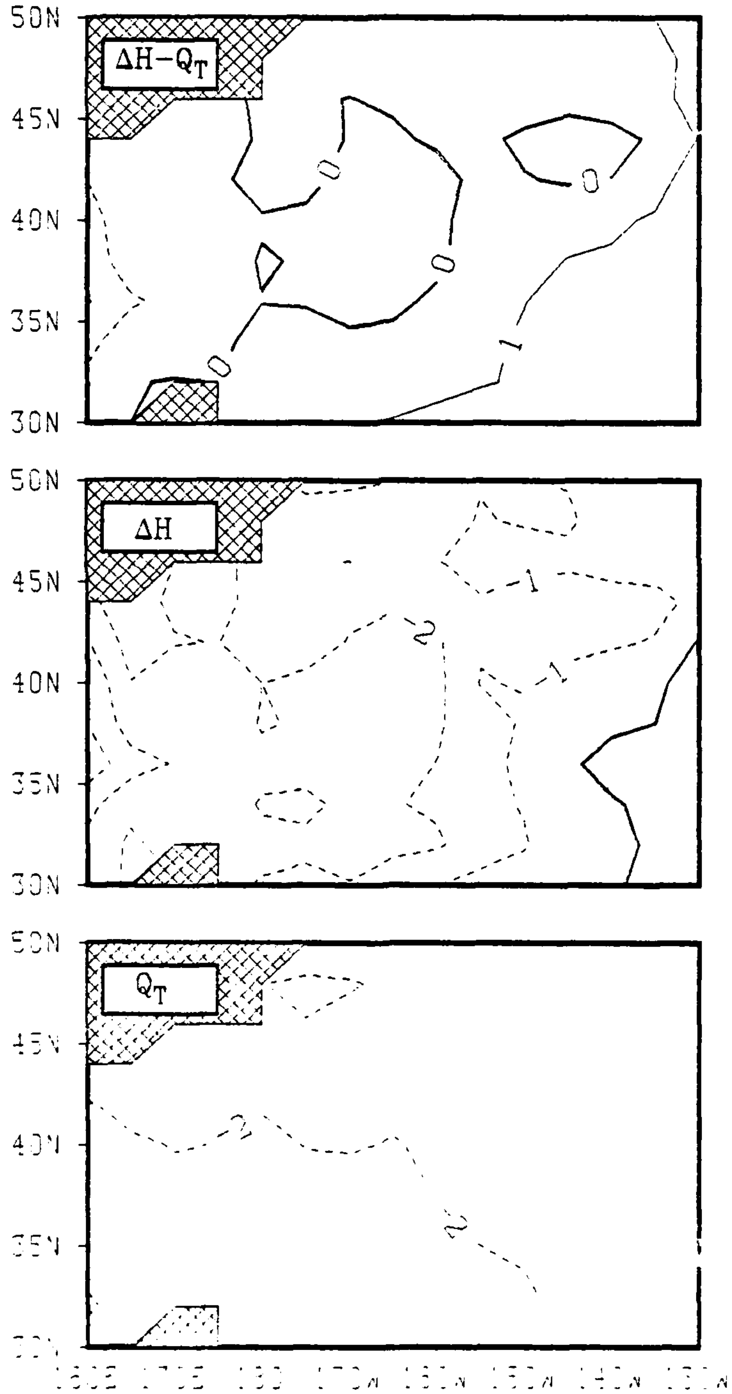

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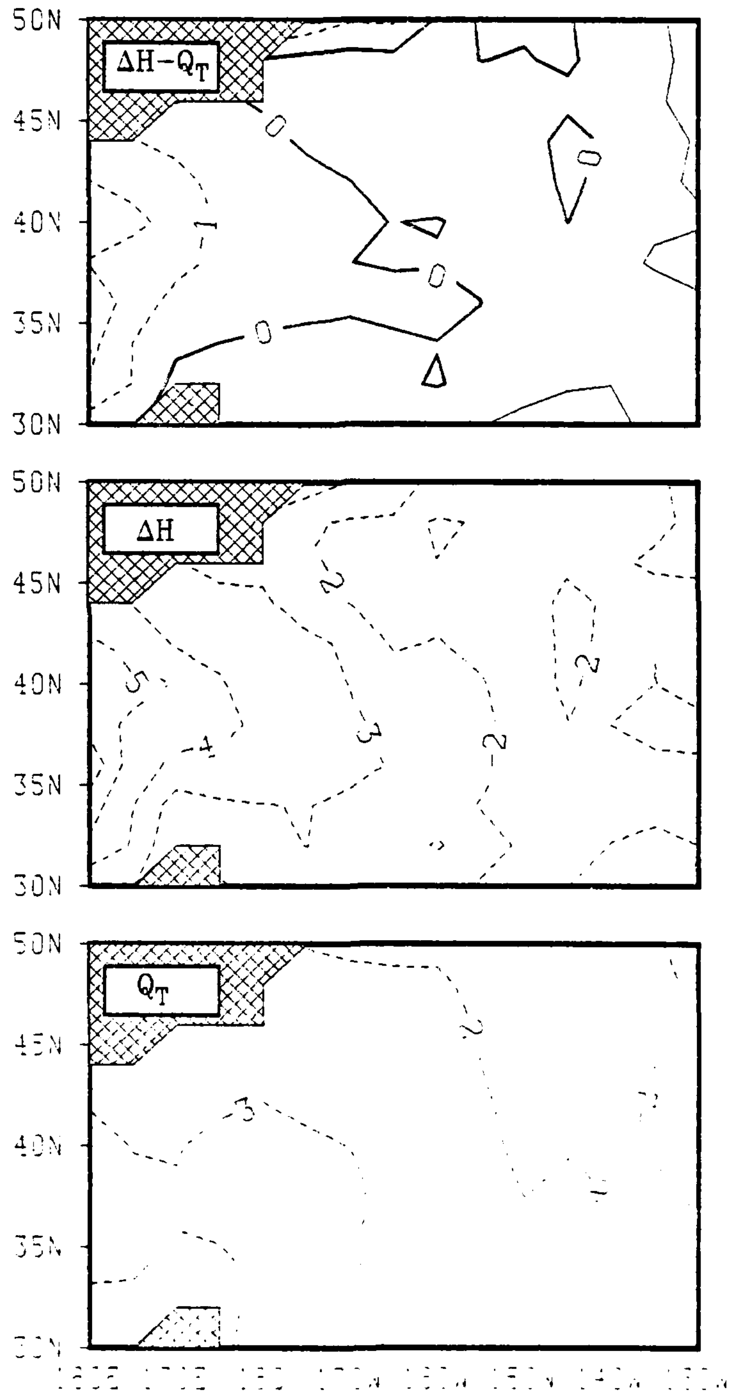

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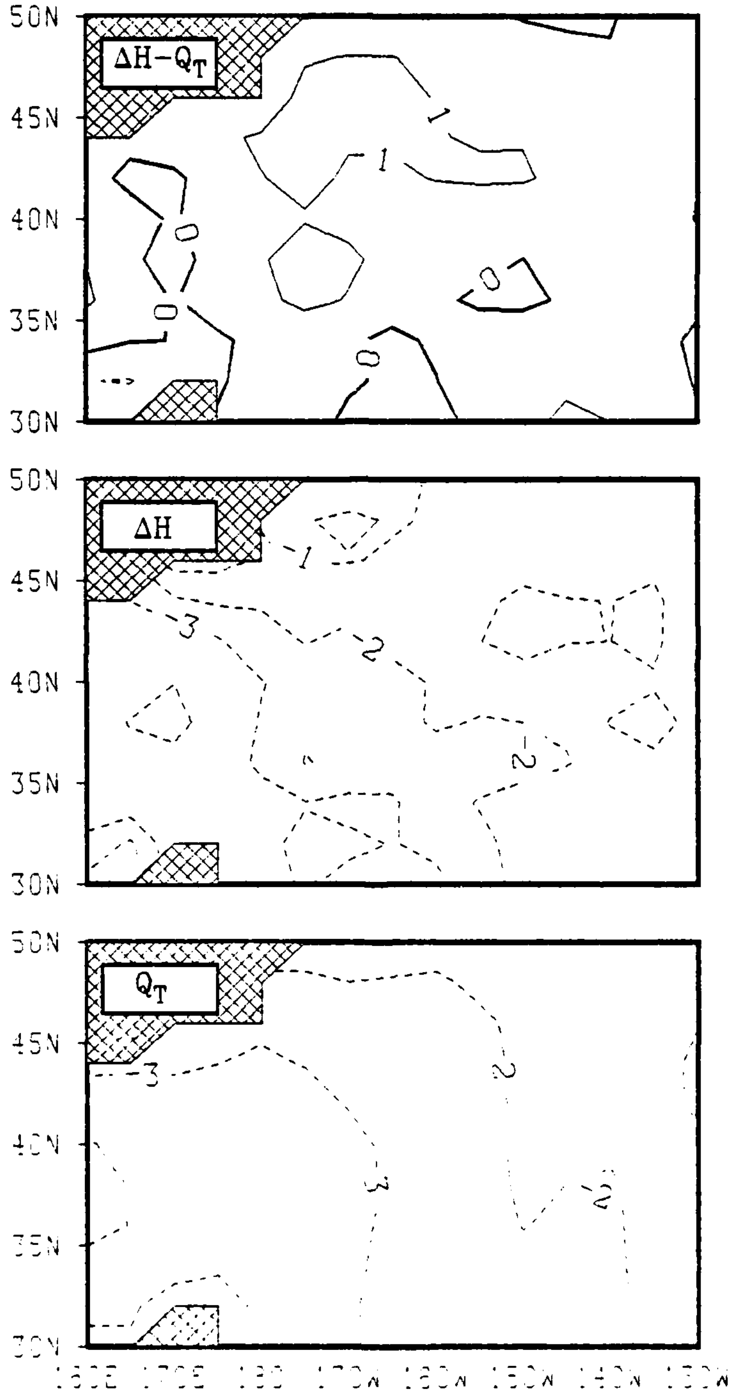
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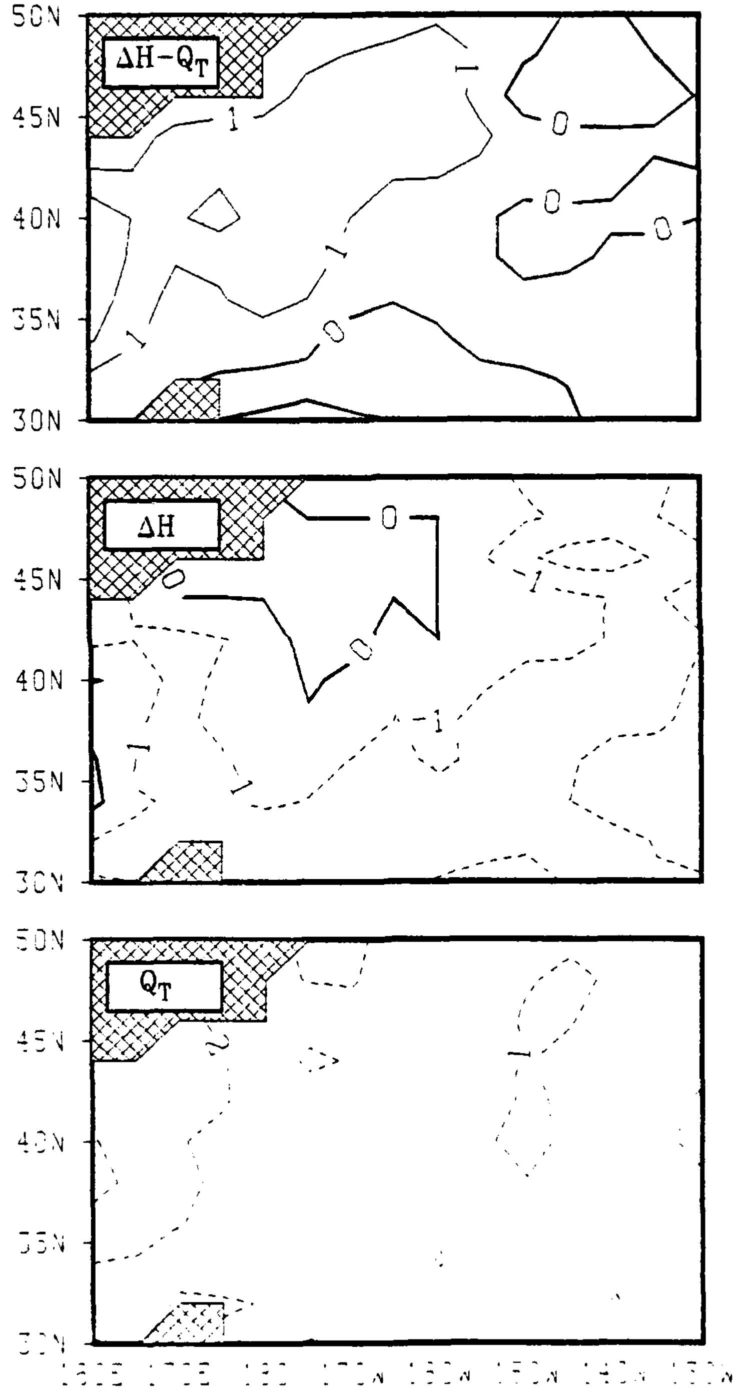

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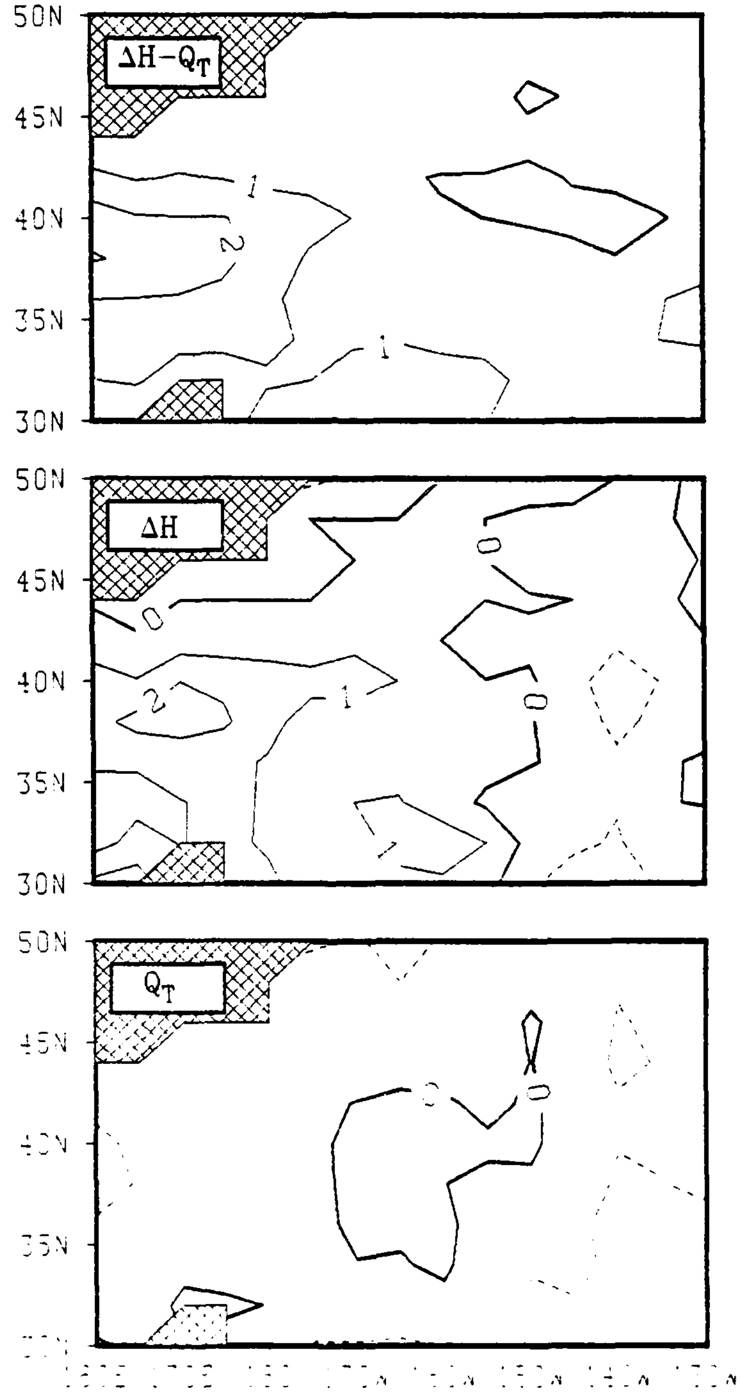

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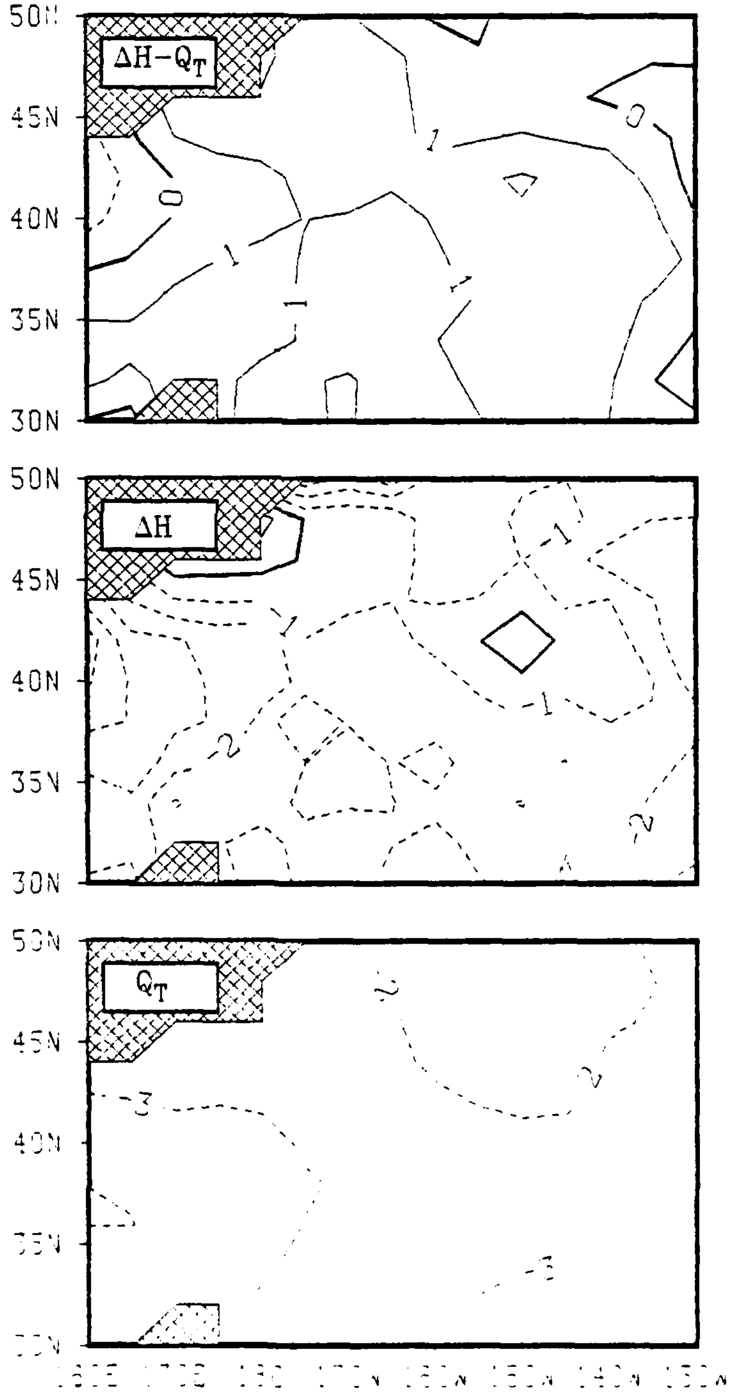

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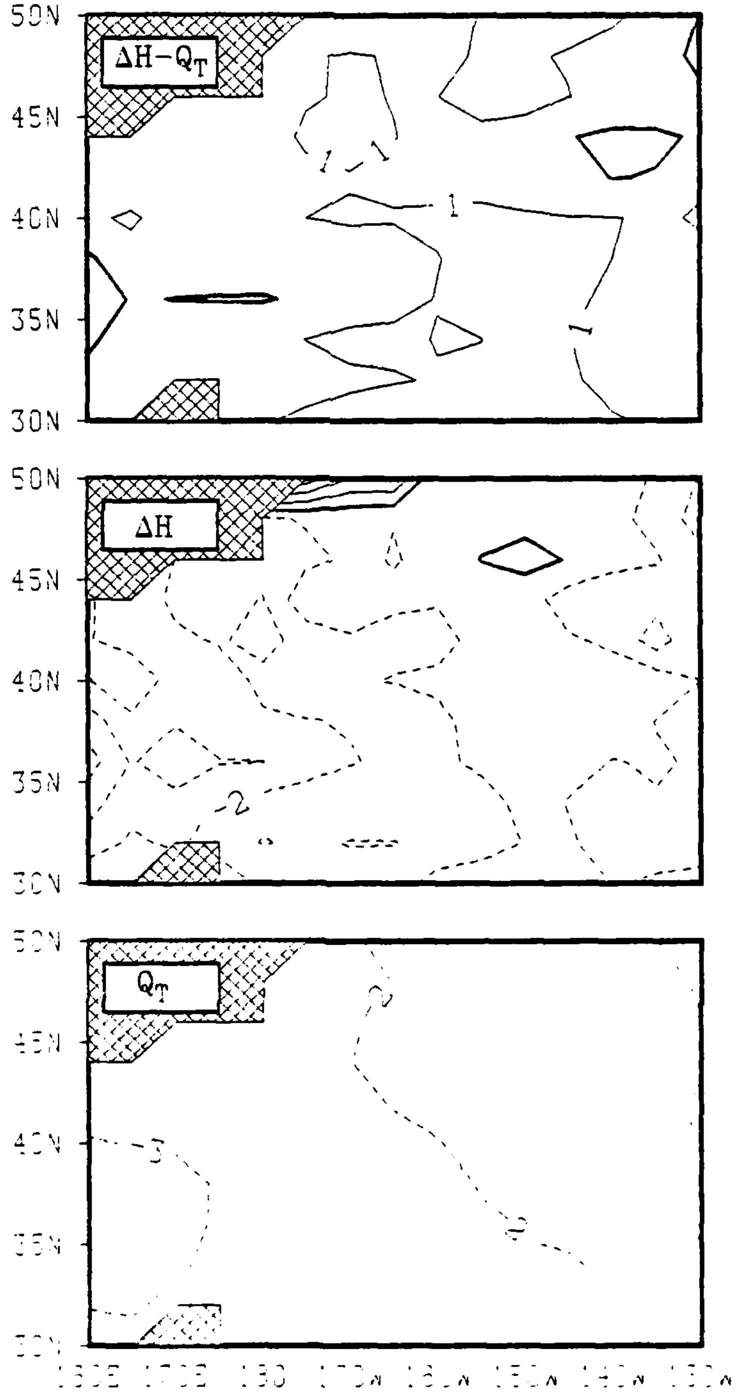

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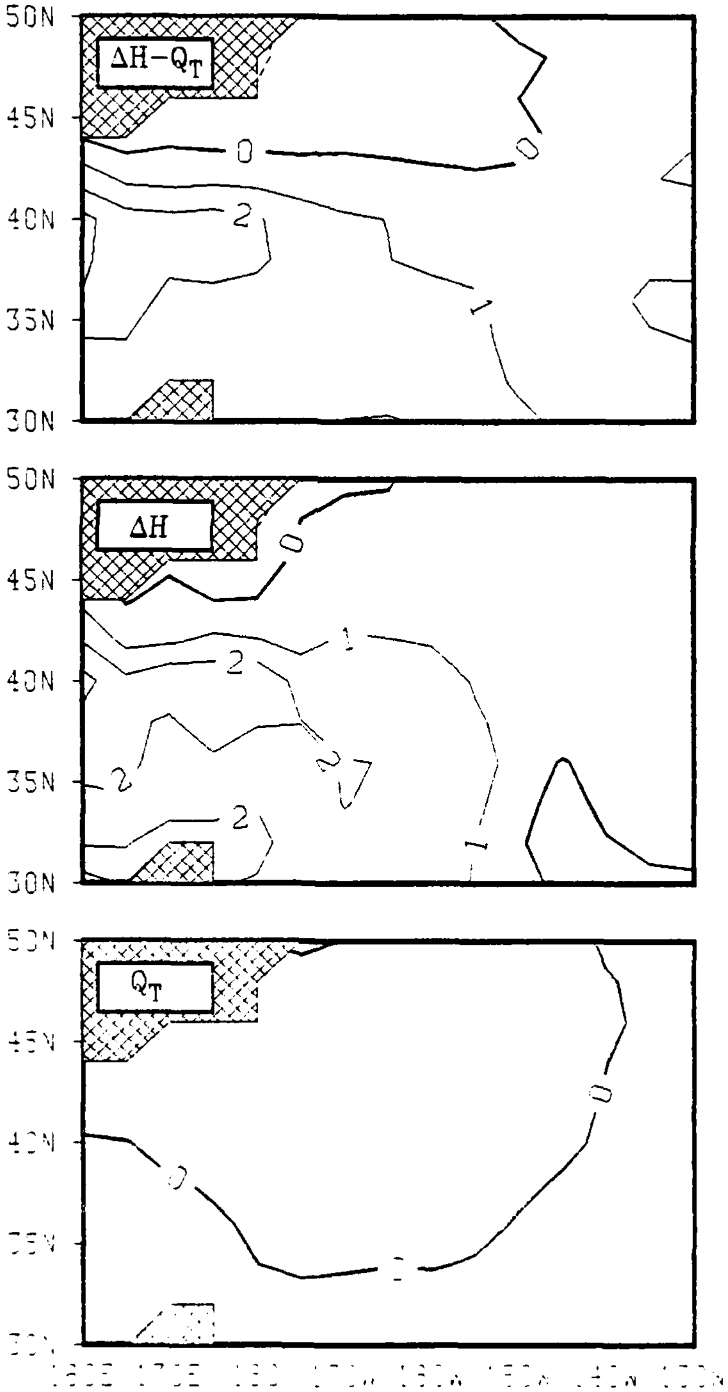

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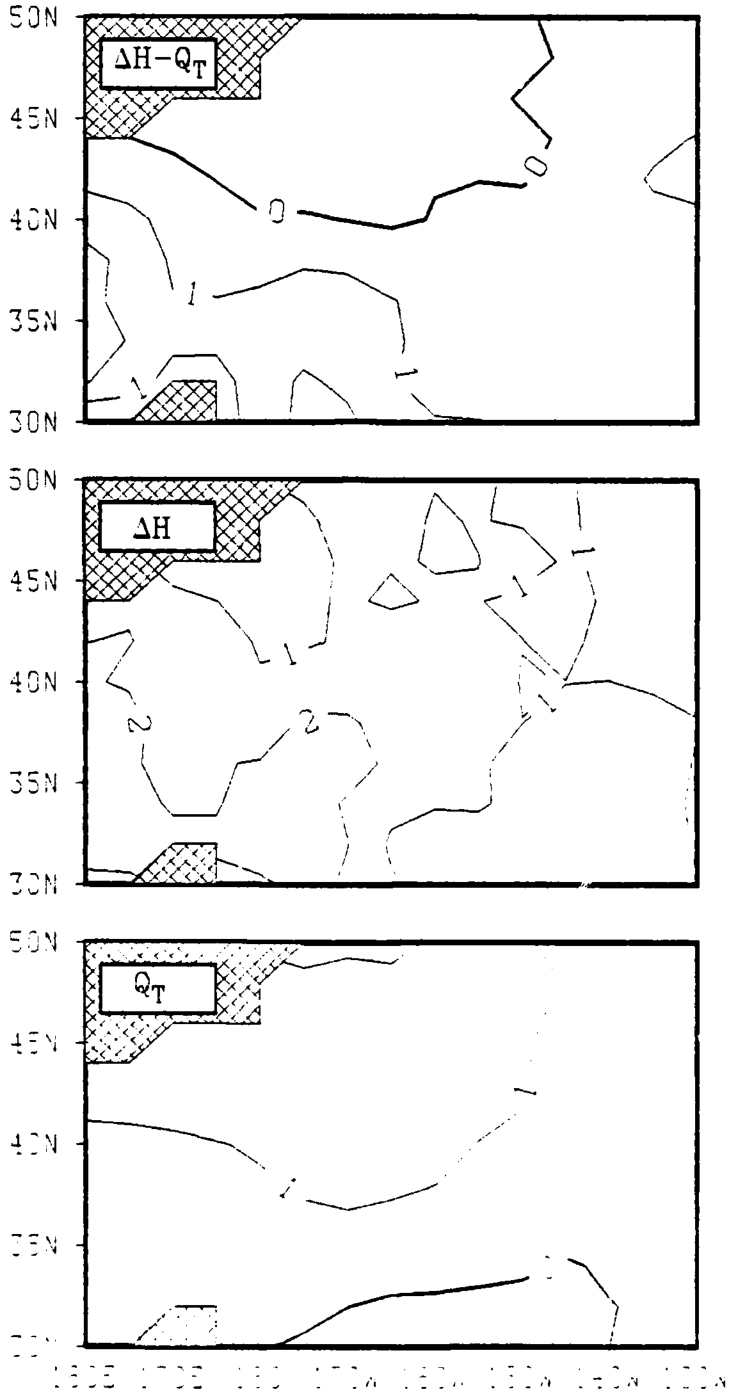

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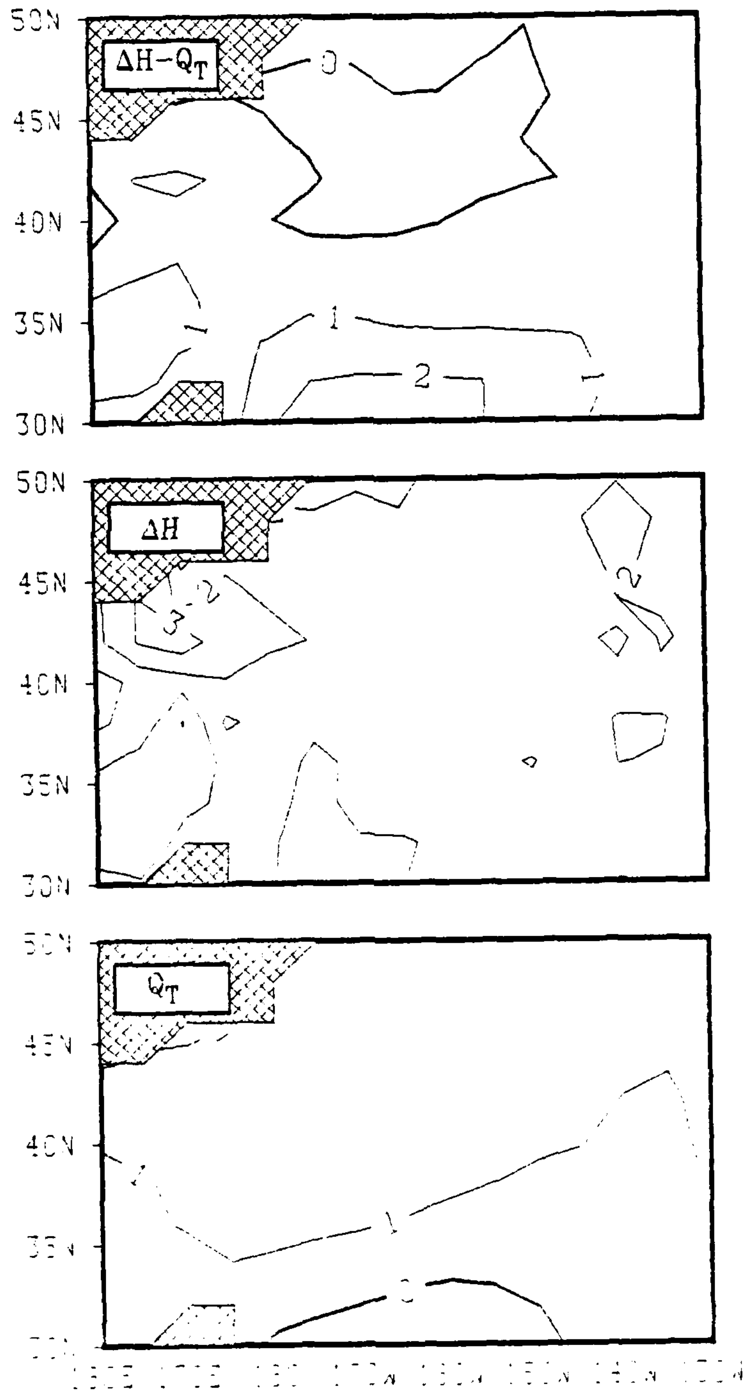

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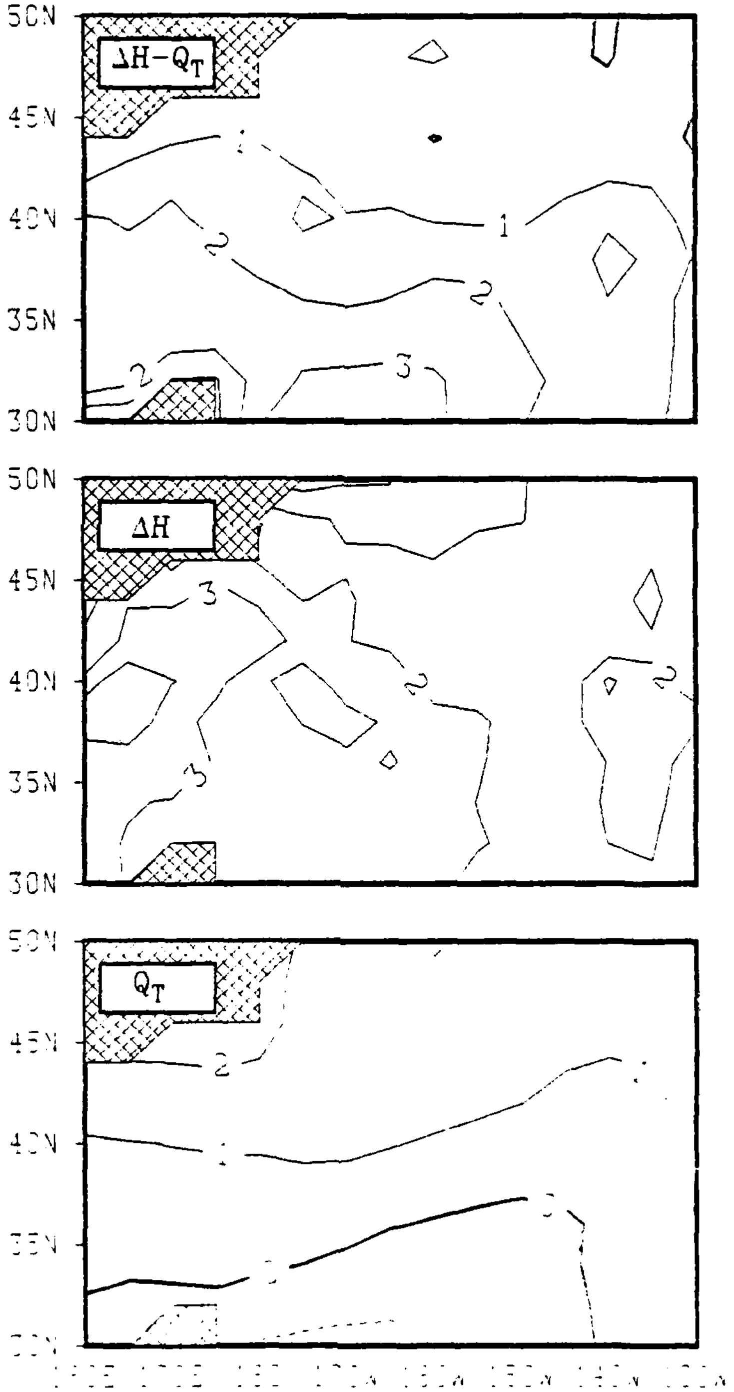

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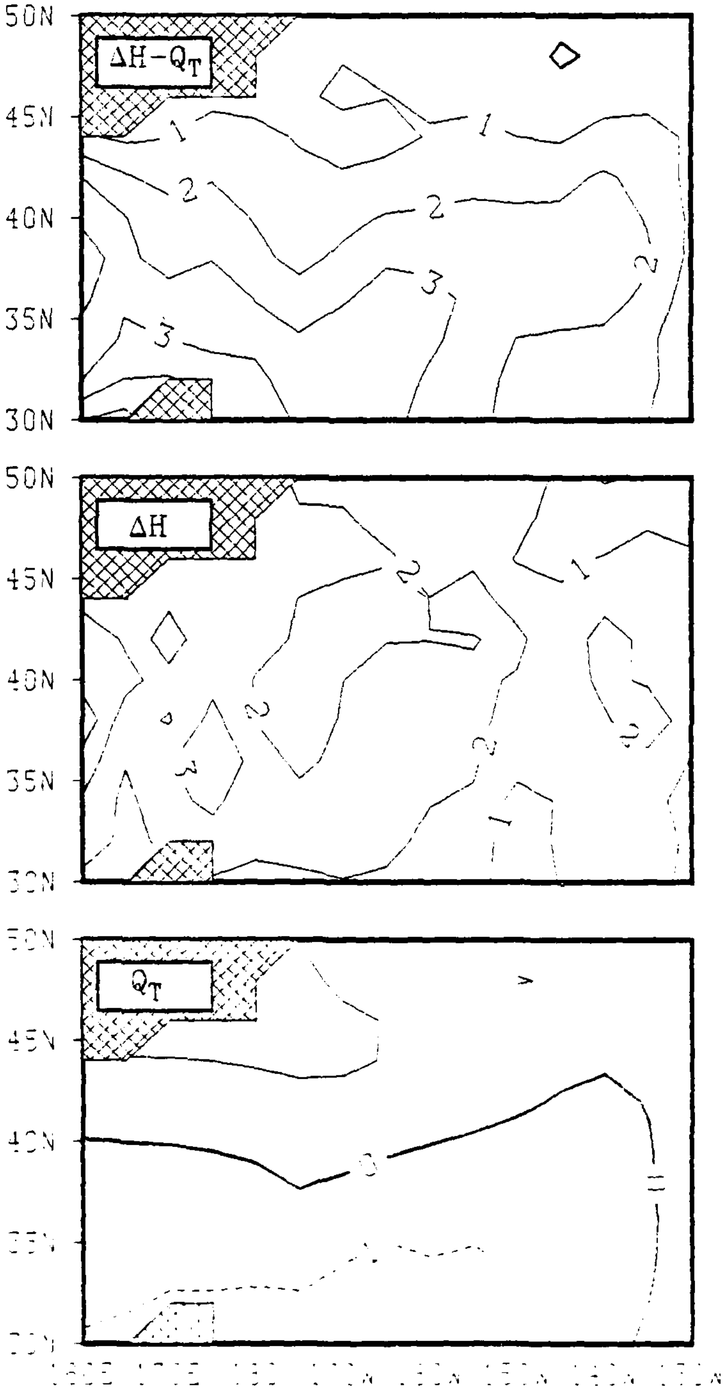

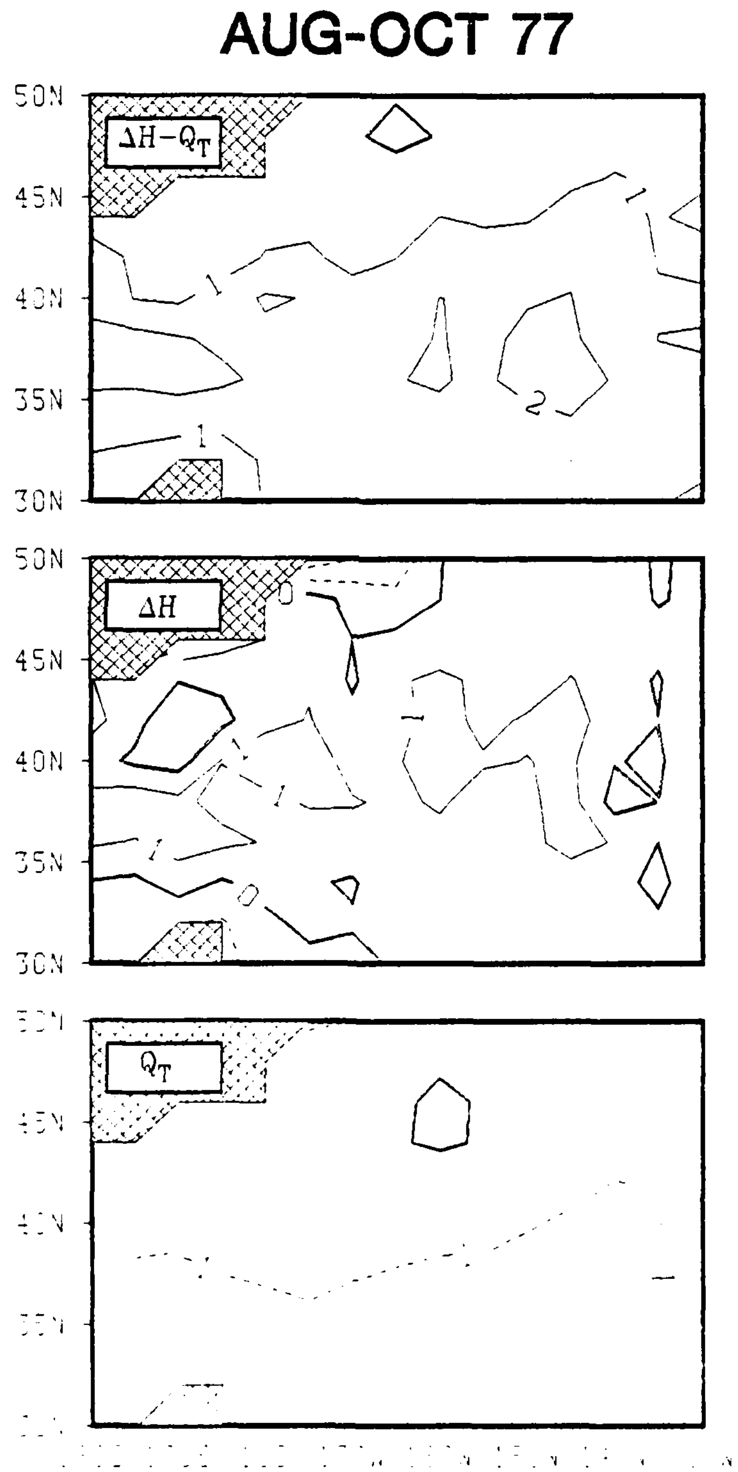

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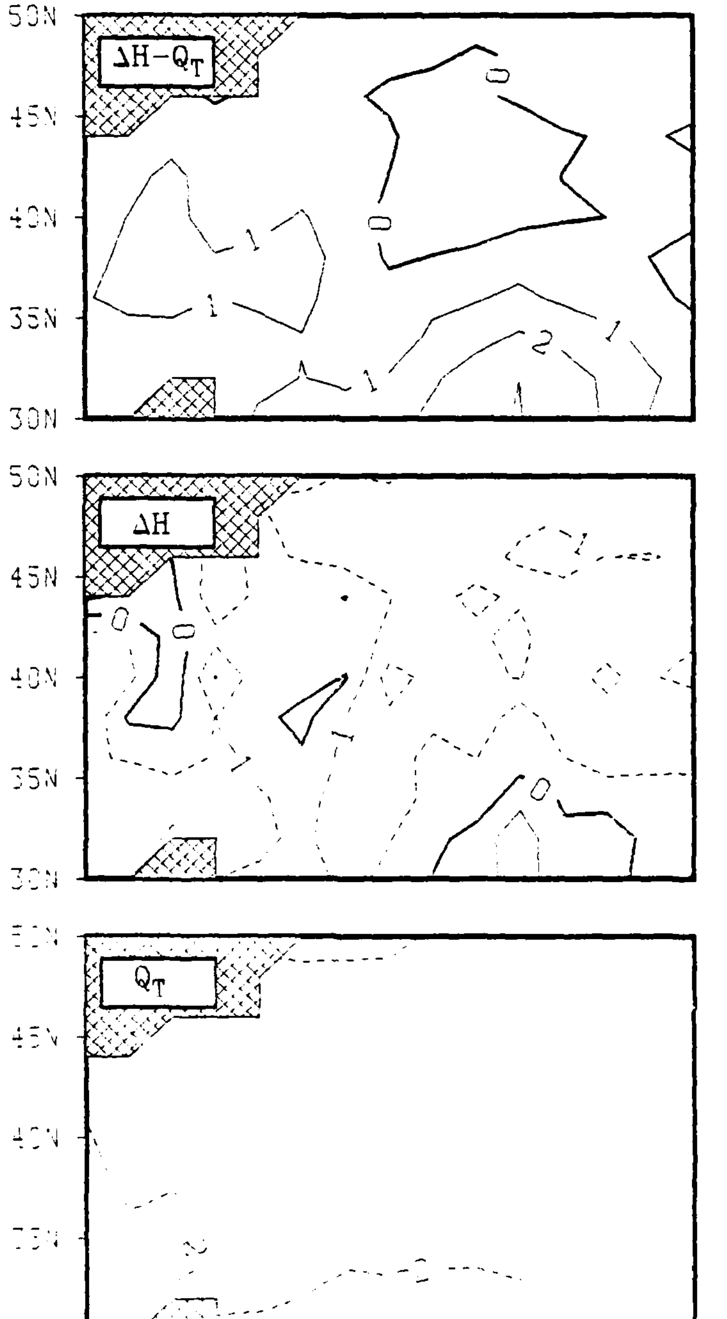

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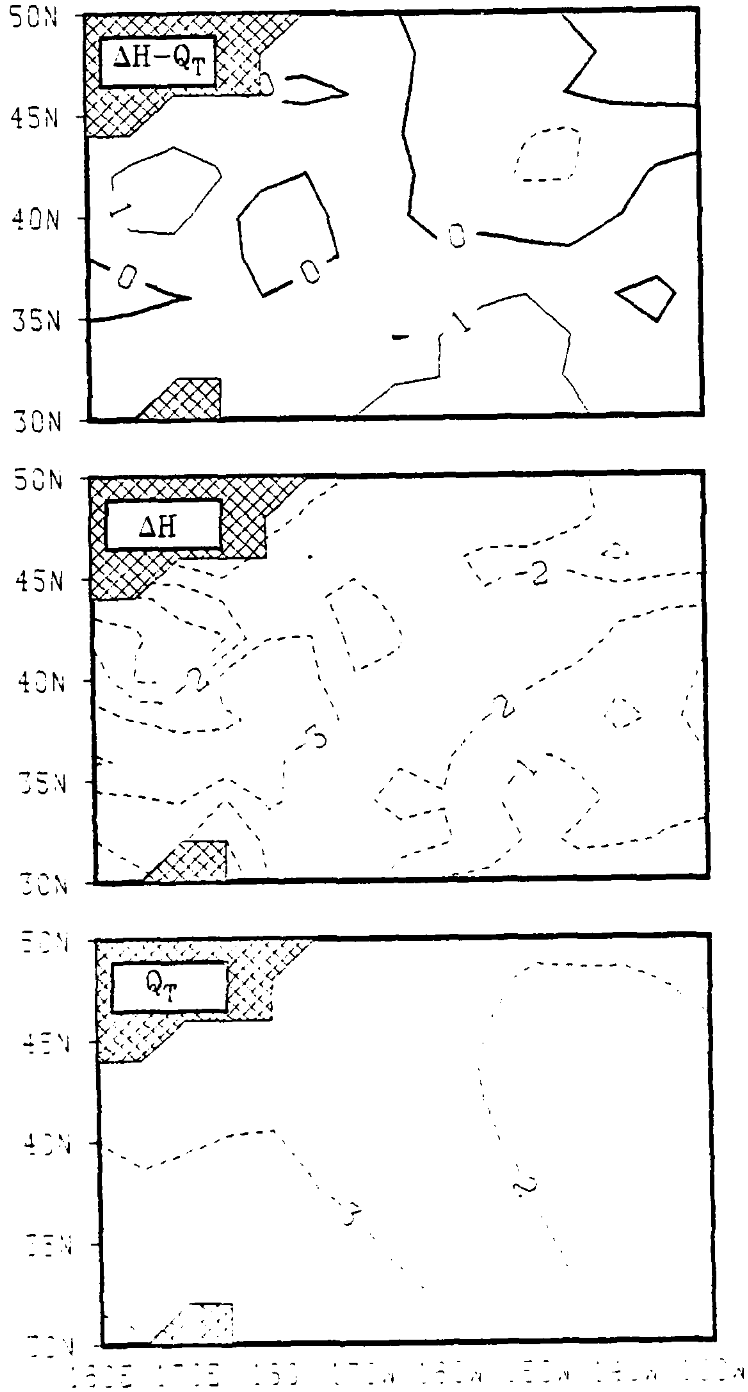

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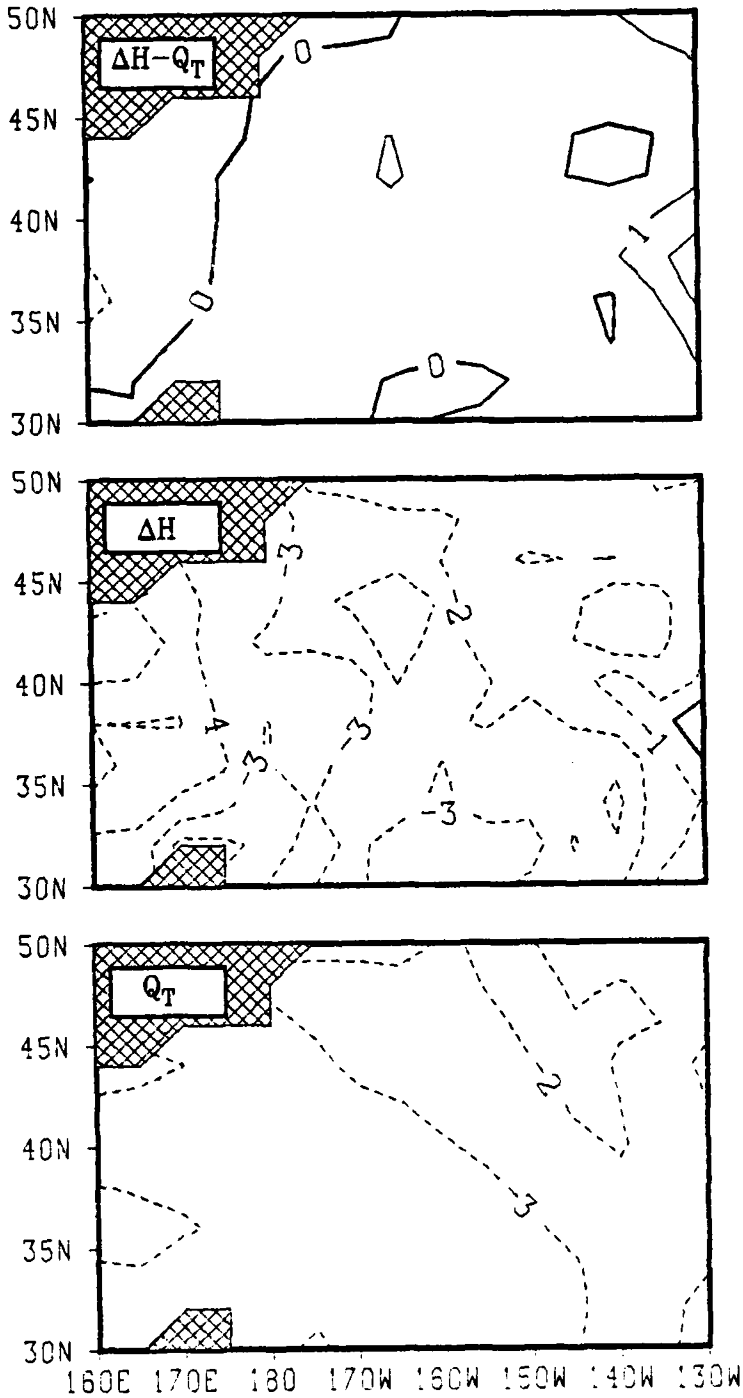

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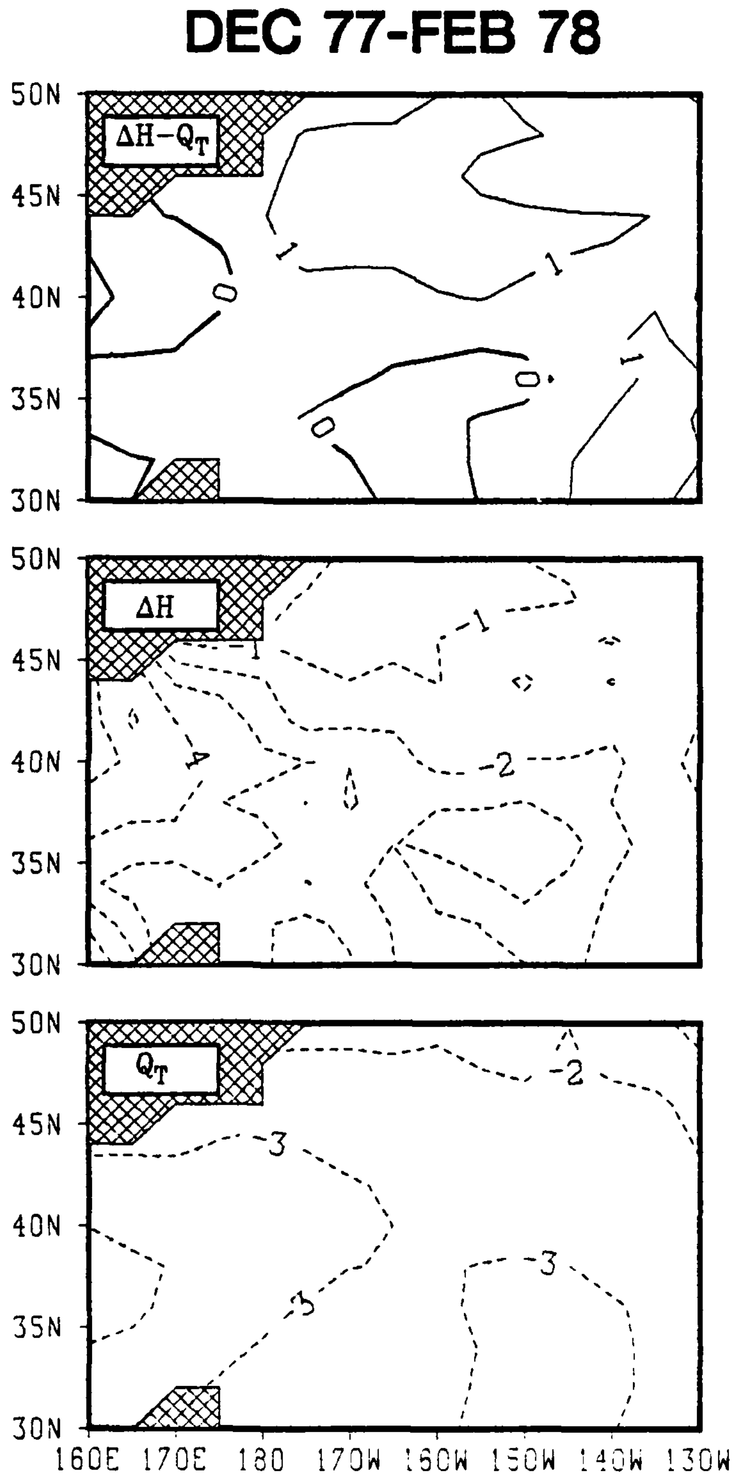

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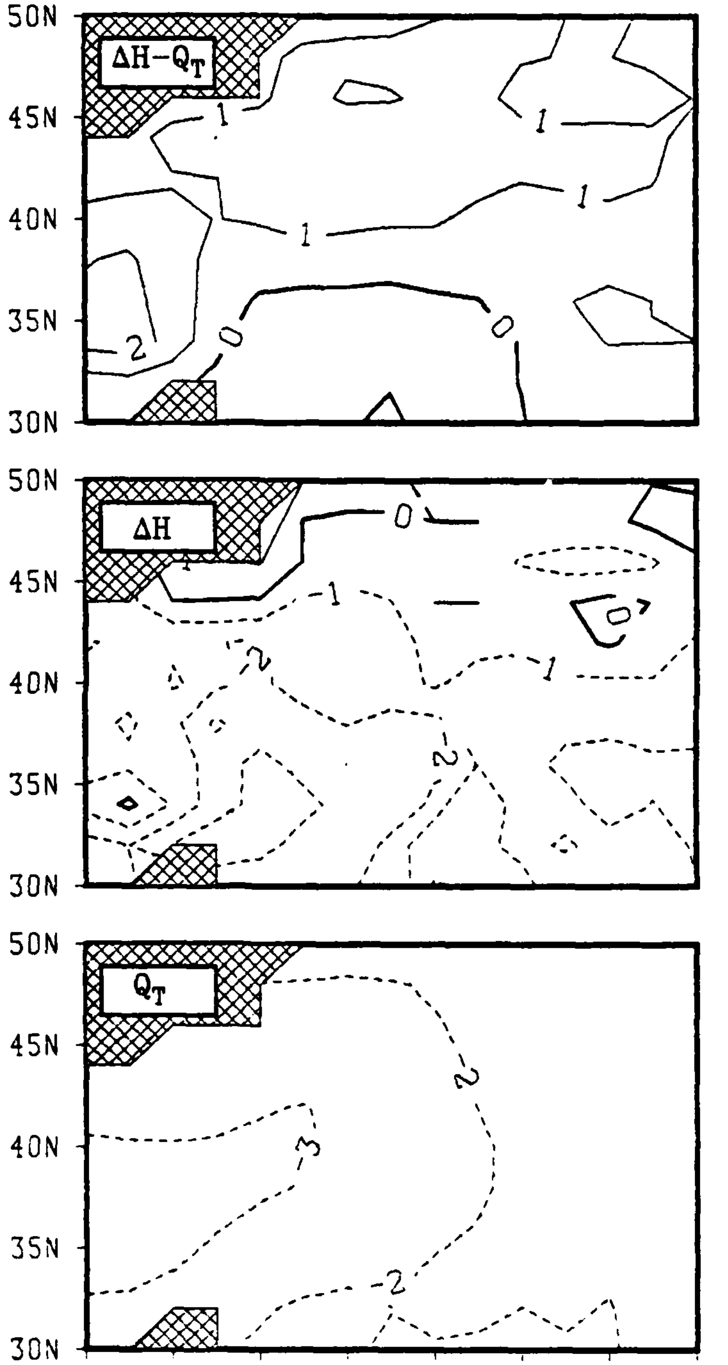

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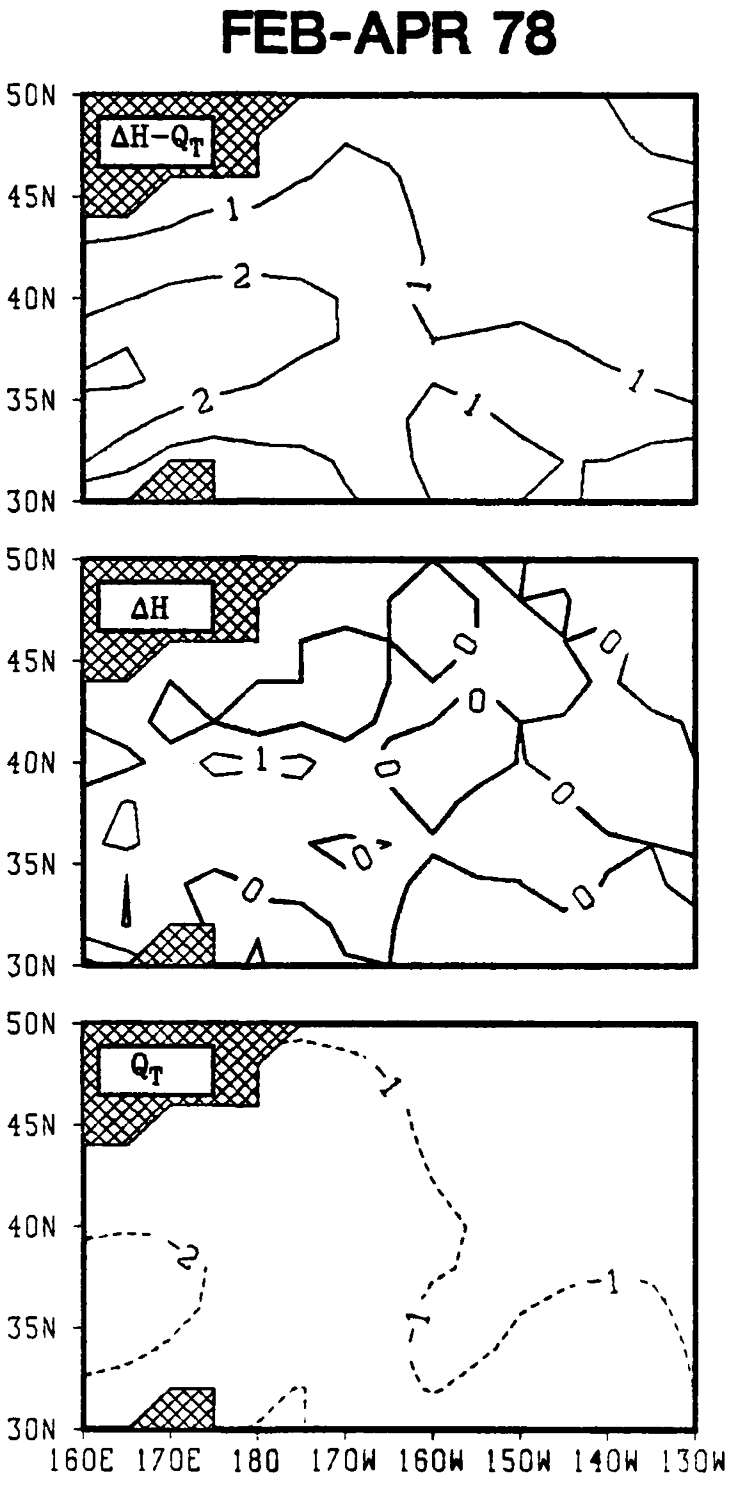

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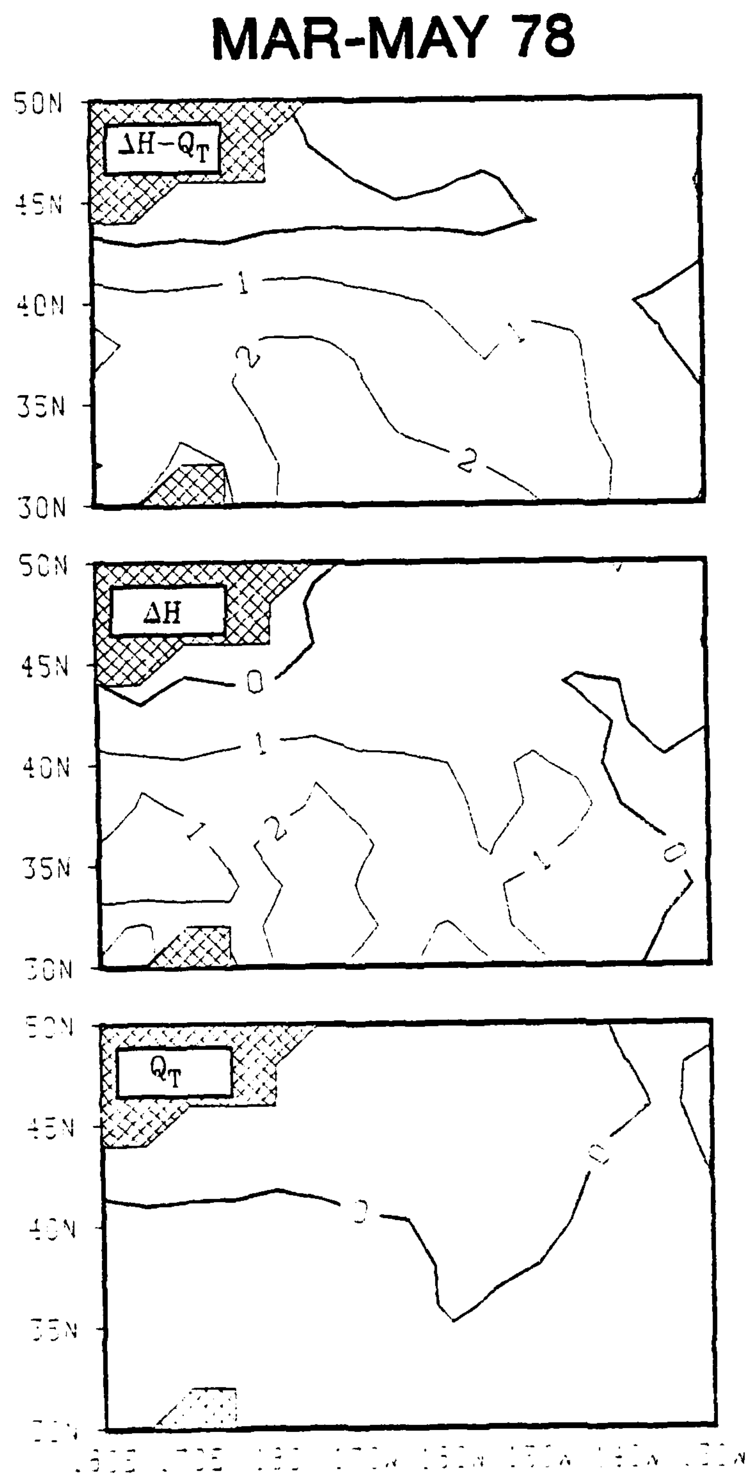
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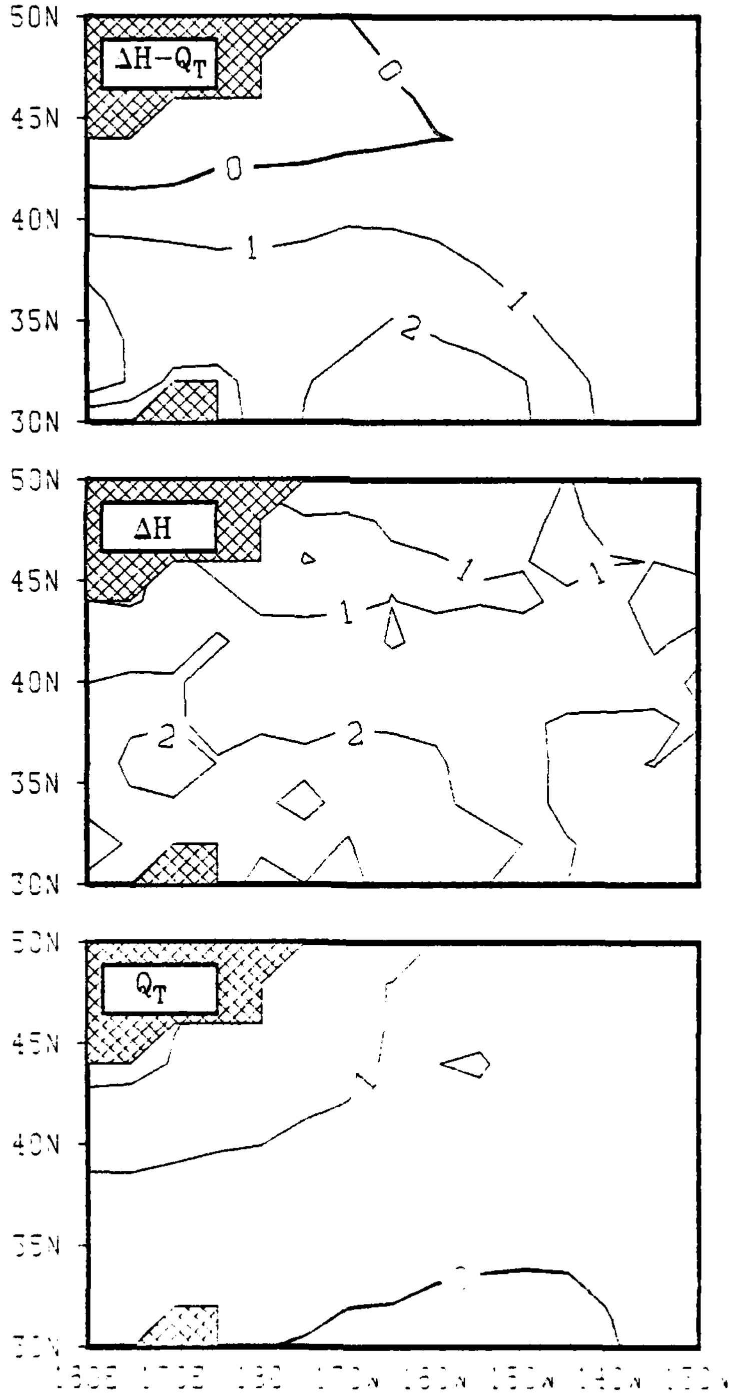

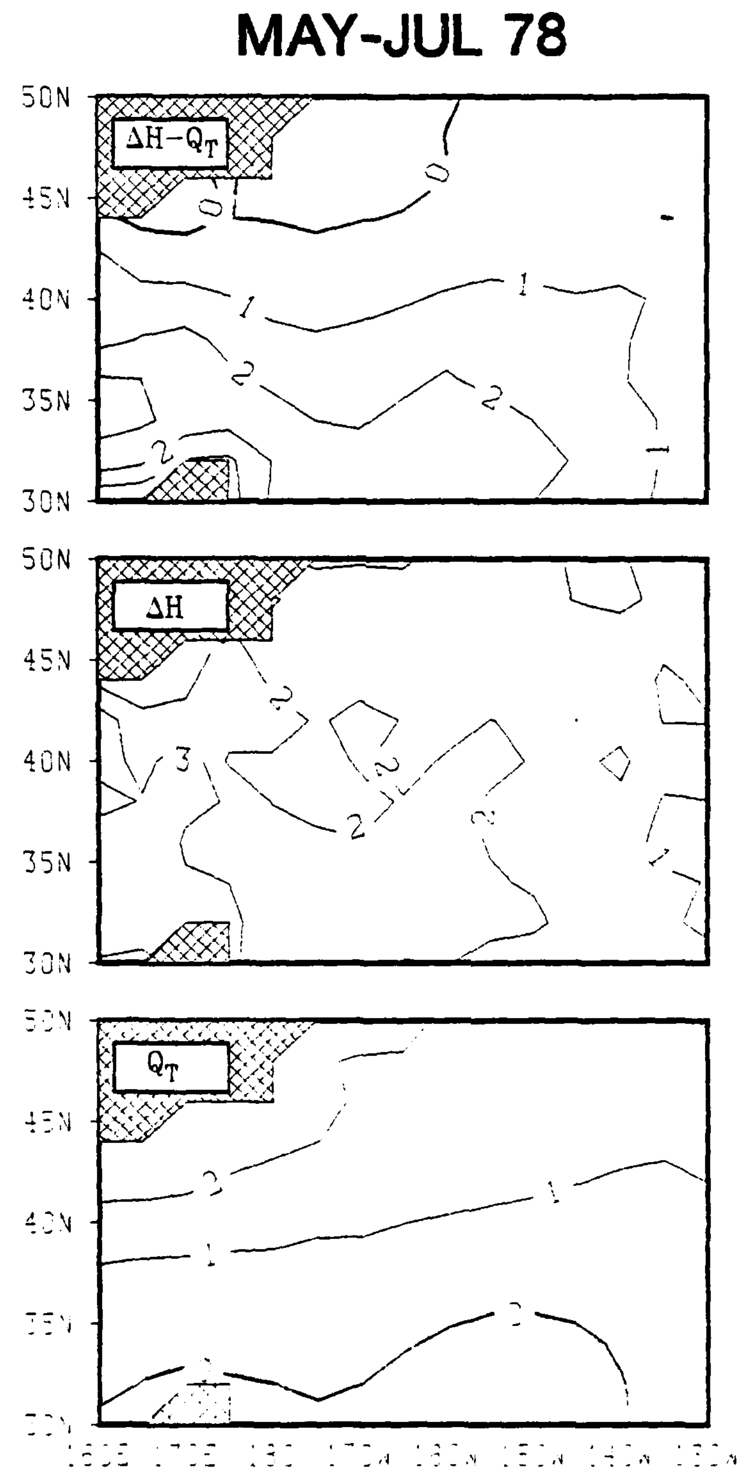
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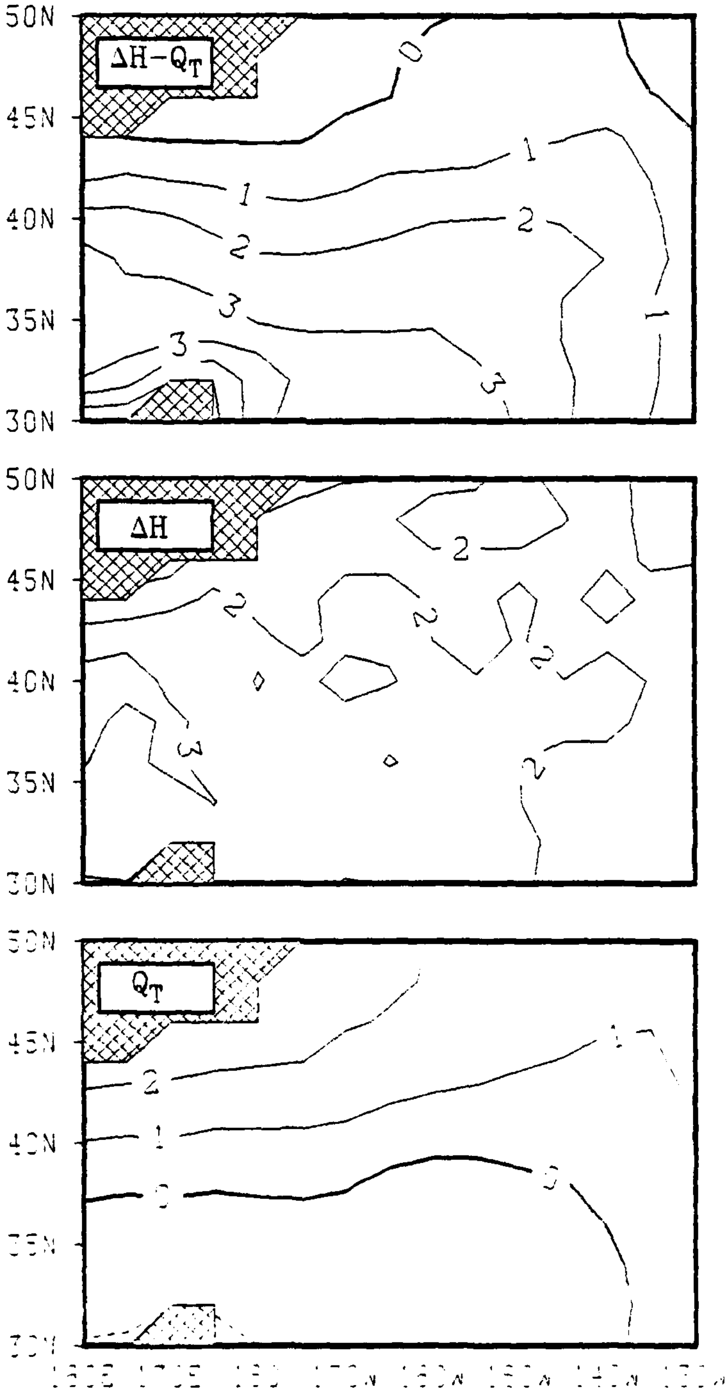

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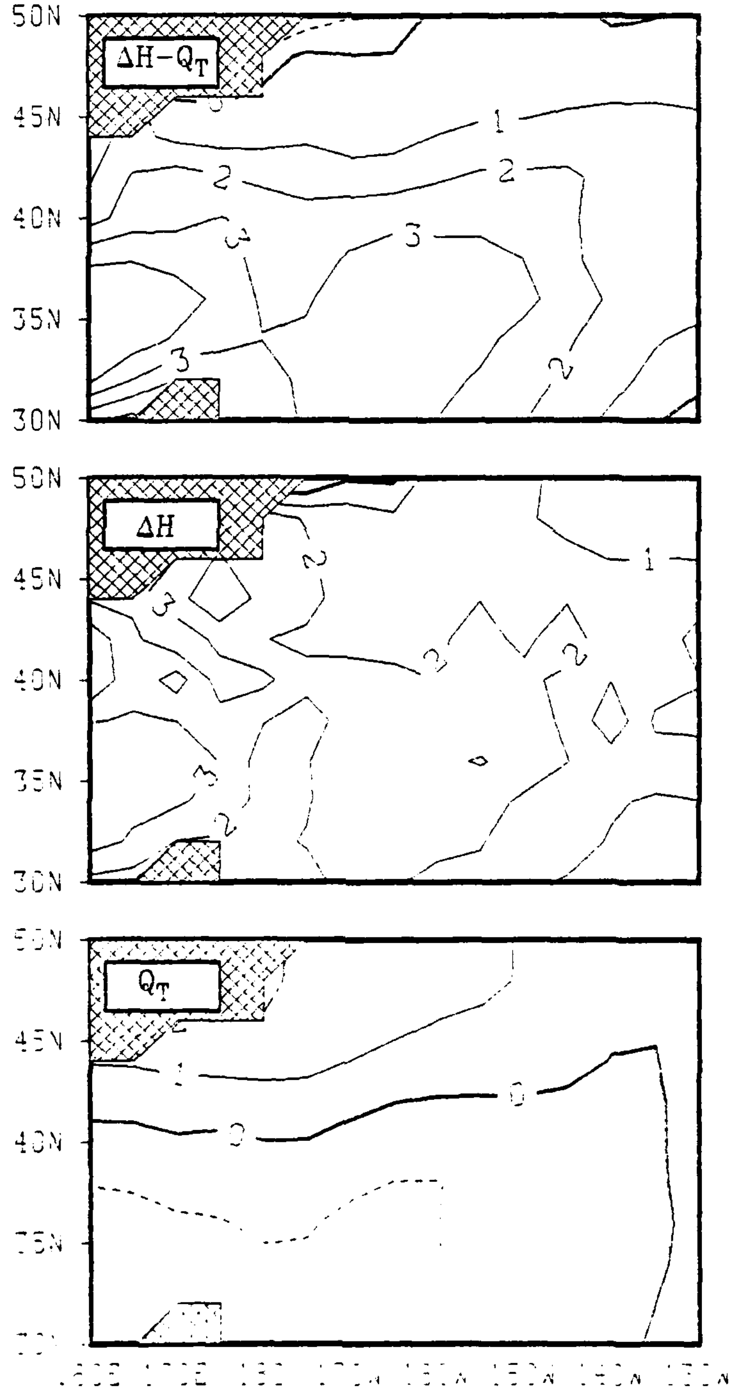

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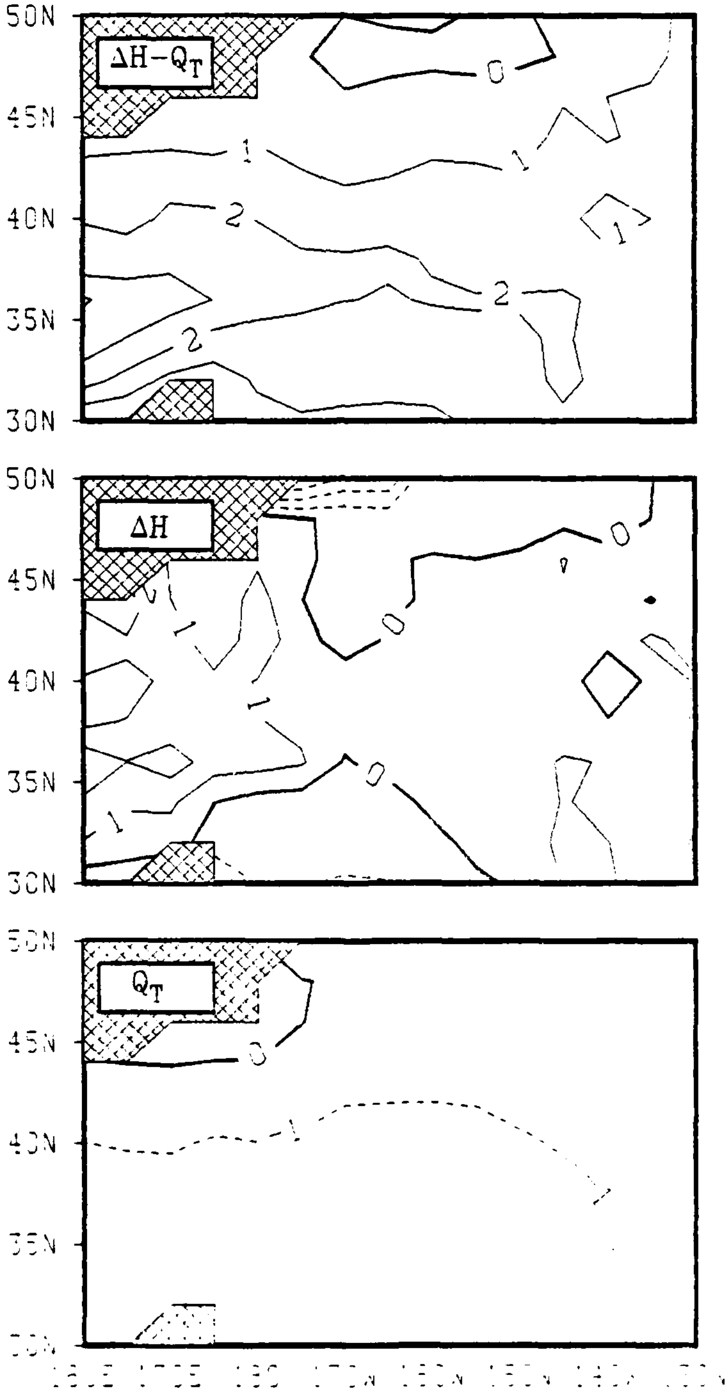

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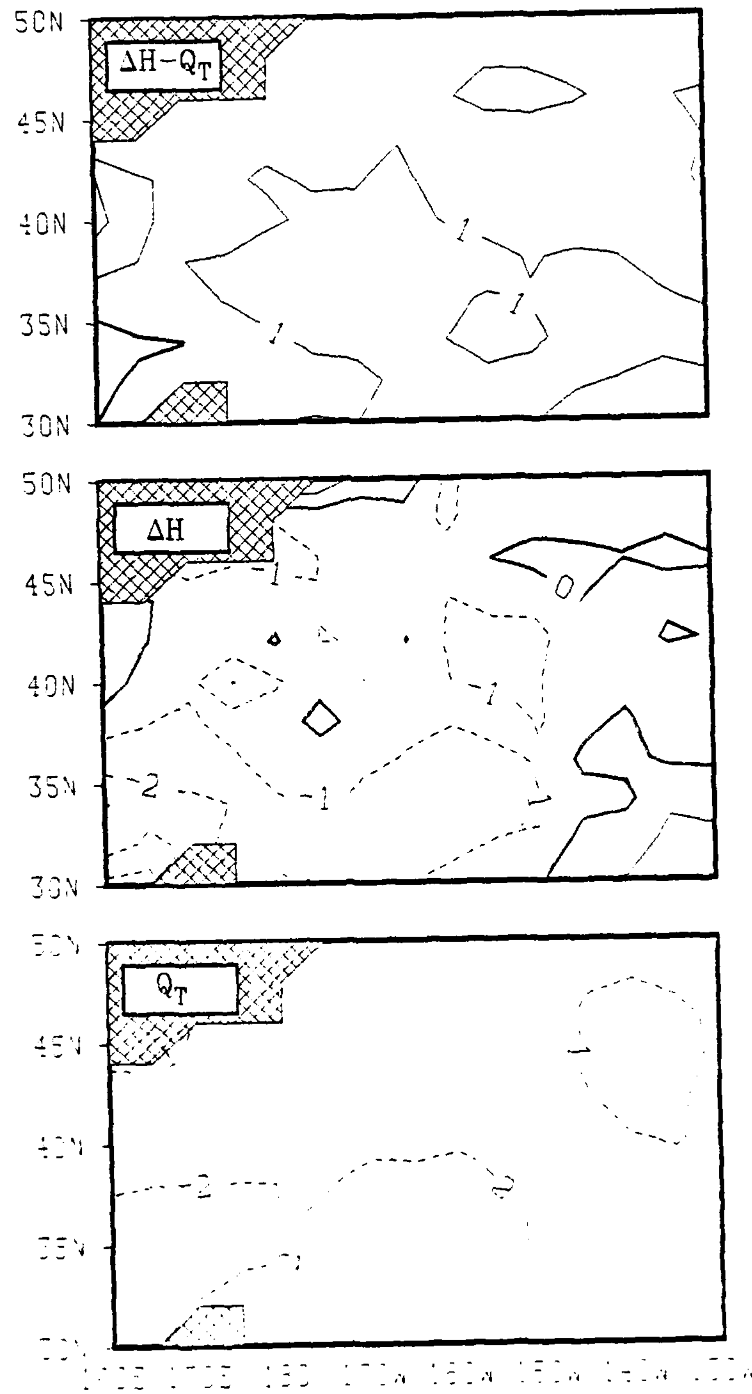

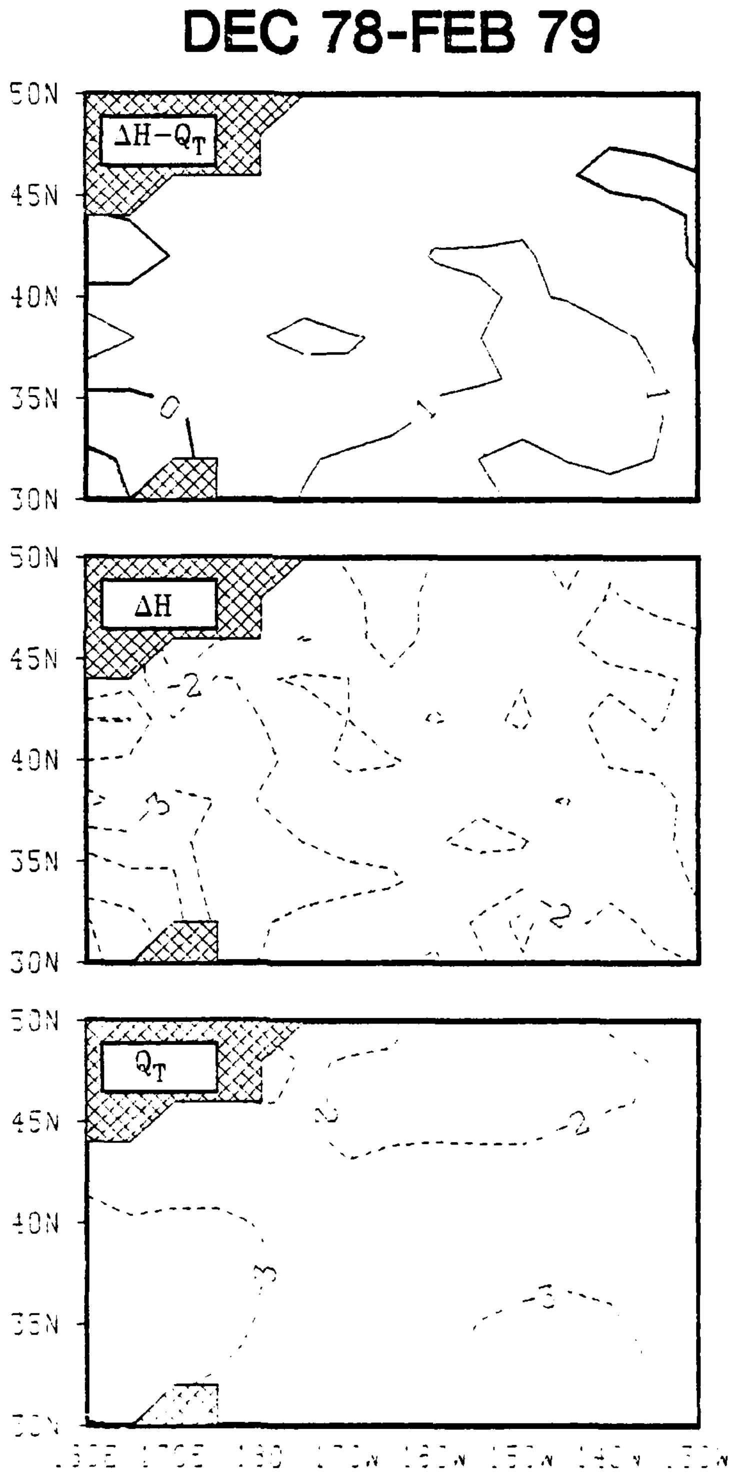

DEC 78-FEB 79
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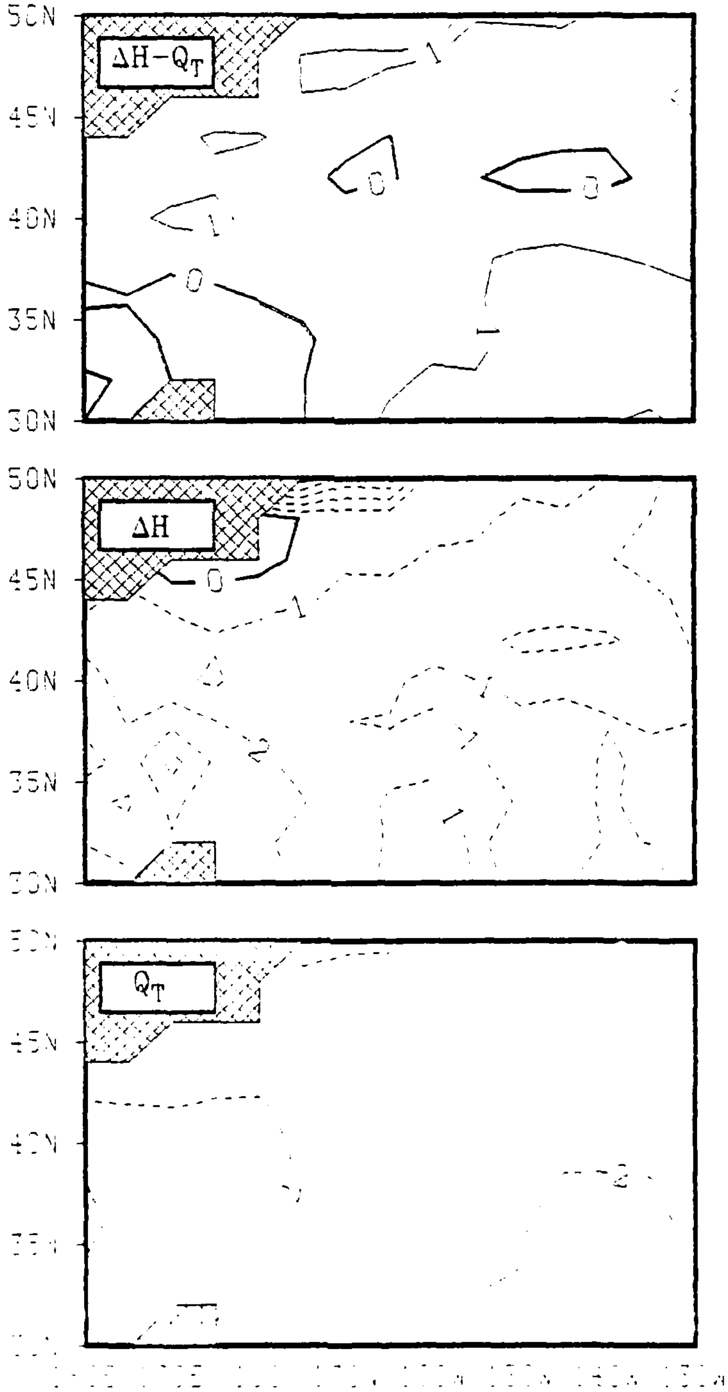
45N
40N
35N
30N
ΔH−Q_T
ΔH
Q_T
0
1
-2
-3

JAN 78-MAR 79



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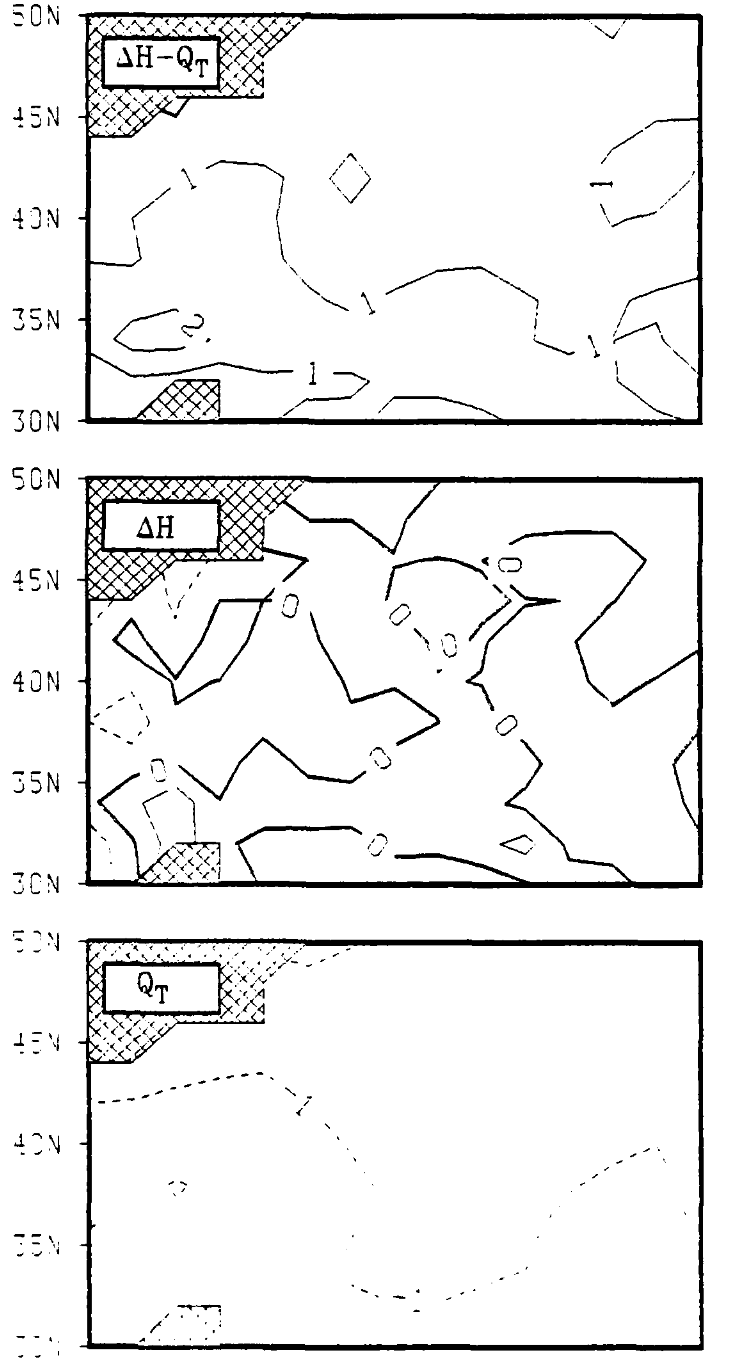

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